Wake-up Radio-enabled Routing for Green Wireless Sensor Networks

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***Abstract*—In this paper we present GREENROUTES, an energy-aware routing protocol for Energy Harvesting-based ("green") Wireless Sensor Networks that leverages self-powered technologies for eliminating the need of energy storage device replacement. GREENROUTES combines energy harvesting and wake-up radios with *semantic addressing*. Semantic addressing capabilities are effectively used to enhance communication by allowing nodes to selectively wake-up a suitable subset of neighboring nodes. This subset is determined by the distance of nodes from the sink, and, greedily, by the residual energy along routes to the sink. The performance of GREENROUTES has been compared to that of the Energy Harvest Wastage-Aware (EHWA) routing solution in scenarios where all nodes harvest energy from the same source, either sun or wind. Results show that GREENROUTES achieves a packet delivery ratio significantly higher (up to 40%) than EHWA, while delivering packets faster and for less power.**

I. INTRODUCTION

The multi-hop and ad hoc networking of a large amount of wireless devices is a communication paradigm that has been recognized as one of the key enablers of rapidly emerging applications, including those that make up the fabric of the Internet of Things (IoT) and Smart Cities. These networks, often called wireless sensor networks (WSNs), are characterized by the low cost of their components, pervasive connectivity, and self-organization features, which allow them to cooperate with other IoT elements to create large-scale heterogeneous information systems. The deployment of WSNs comes with a number of limitations, such as the severe power constraints and limited resources of the network devices. As an outcome, a number of considerable challenges is arising when considering the design of large-scale WSNs, including energy-efficient operations, routing, and unreliable communication links.

The challenging problem of limited battery capacity and energy efficiency is present in a tremendous amount of WSN-based IoT applications. Research on WSNs is now considering networks made up of self-sustainable devices [1], [2], each aiming at minimizing any form of on-board energy consumption and that are capable of harvesting energy from multiple surrounding sources. In fact, Energy Harvesting-based Wireless Sensor Networks (EH-WSNs), often also dubbed *green networks*, are considered a fundamental vehicle for enabling all those critical IoT applications where devices, for different reasons, do not carry batteries, and that therefore only harvest energy and store it for future use. EH-WSNs are considered to have the potential of infinite lifetime since they do not depend on battery, or on any other limited power source.

Another promising approach that assists on overcoming the physical constraints of WSNs is that of the emerging low-power radio triggering techniques, such as the wake-up radios [3], [4]. Wake-up radios are governed by the following principle: Devices within the wake-up communication range of the sender of data, wake up only when they receive a wake-up sequence. In this way devices turn on their main transceiver only in cases when they have to transmit or receive packets. During the rest of the time, their main transceiver remains off, achieving a remarkably reduction of energy consumption, often of two or three orders of magnitude [3]. Exploiting further their beneficial features, *semantic addressing* can enhance performance by allowing devices to selectively wake-up a subset of neighboring devices based on their current status. Particularly, multiple wake-up addresses can be assigned to a device. This set of addresses is dynamically updated based on changes of the node and in the network. It has been shown that on-demand waking up can remarkably improve system performance by breaking the energy-latency trade-off [3], [5]. Wake-up radio approaches are particularly important in EH-WSNs scenarios in which it is difficult to achieve energy neutrality due to limited harvesting rates.

Based on the above discussed challenges, issues and advances, more research efforts are required for making the vision of WSN-based IoT a reality. Particularly, routing protocols for green networks need to be designed that draw benefits from the joint exploitation of wake-up radio technology and energy harvesting. In this paper we propose GREENROUTES, a novel energy-aware cross-layer routing protocol for wake-up radio-based green networks. GREENROUTES is based on the idea of using semantic addressing to select as data forwarders (relays) the "best" neighboring devices through the transmission of wake-up sequences. Each device (called node in the rest of the paper) is assigned two wake-up addresses. The first wake-up address is set based on its distance (in hops) from the data collection point (the sink) and on a dynamically updated estimate of the energy available on the most recent route to the sink. The second wake-up address corresponds to the node unique identifier (ID), according to some set network naming.

We compare the performance of GREENROUTES with the wake-up version of a routing solution specifically designed

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for EH-WSNs, namely, the Energy Harvest Wastage-Aware (EHWA) protocol [6], for varying parameters such as data traffic and energy harvesting sources, namely, solar and wind. Our GreenCastalia-based [7] simulation results show that, through the clever combination of energy harvesting and wake-up radio capabilities, GreenRoutes achieves a packet delivery ratio that is up to 40% more than that of EHWA, an end-to-end latency consistently lower than that of EHWA (up to 3.5 times lower), and an overall energy consumption that is a fraction of the energy spent by EHWA (up of over a half).

The remainder of the paper is organized as follows. Section II summarizes works on routing EH-WSNs and for wake-up radio-based networks. In Section III we describe the GreenRoutes protocol. A comparative performance evaluation of GreenRoutes and EHWA is provided in Section IV. Finally, Section V concludes the paper.

II. RELATED WORK

Several routing protocols for WSNs have been proposed with the fundamental nature of energy harvesting in mind [1], [2]. Because of the uncertainty of the energy harvesting rates research has headed towards the design of protocols that consider these variations when routing packets. In this direction, the authors in [6] present an energy wastage-aware route selection protocol for EH-WSNs, named the Energy Harvest Wastage Aware (EHWA) protocol. EHWA is an on-demand dynamic source routing (DSR) protocol that aims at minimizing the energy wastage due to battery overcharging. However, due to the high volume of broadcasting packets that is required by the mechanism of DSR to forward packets, such solutions could lead to high energy consumption.

Lower energy consumption and longer lifetimes can be achieved by adopting techniques that allow nodes to switch their radio from on to off whenever nodes are in an "idle" state according to the preset duty cycle, thus drastically reducing power consumption. In [8], the authors present a solution specifically targeting on networks solely powered by ambient energy harvesting, in which nodes have no long-term energy storage. They propose OR-AHaD, a routing scheme with duty cycling that acts in an energy-aware adaptive manner, by taking into account the short-term estimated harvesting rate to adjust nodes duty cycle. Han. et al. [9], design a cross-layer optimized geographic routing that blends duty cycling and energy harvesting techniques to balance energy consumption. However, despite the value proposition of duty-cycling techniques, when a node is awaken, a significant amount of energy is wasted while waiting to receive data.

Although emerging low-power radio triggering techniques are now considered a promising approach that assists on overcoming the physical constraints of WSNs, there is a limited number of works focusing on the design of routing solutions that adopt wake-up radios. In [10], the authors extend the standard protocol CTP to the use of wake-up radios, and present CTP-WUR. A simple and energy efficient cross-layer routing protocol for wireless sensor nodes with wake-up receivers, called T-ROME, is presented in [11]. Routing in T-ROME is done in a tree-forwarding manner. Specifically, packets are forwarded from a node to its parent node only. In [3], the authors introduce ALBA-WUR, a cross-layer protocol that takes advantage of wake-up radio technologies. All the aforementioned works, however, do not implement energy harvesting solutions, and cannot be considered energy-aware since they do not take into account information related to the energy state of a relay node.

III. THE GREENROUTES PROTOCOL

GreenRoutes is a cross-layer protocol, where each node that has a packet to transmit performs channel access and next-hop relay selection jointly. The selection of relay nodes is based on their distance (in hops) from the sink, and, greedily, on the energy available along routes to the sink. To describe the operations of our protocol in networks using wake-up radios with semantic addressing capabilities, we start by explaining how nodes determine their own wake-up addresses, and then we indicate the actions performed by a sender node to forward a data packet.

Wake-up address determination. The wake-up address w^i of a node i is obtained by juxtaposing the two binary sequences w_ℓ and $w_{\epsilon^i_\ell}$, representing the node hop distance from the sink $\ell \geq 1$, and an estimate of the energy ϵ^i_ℓ available on the most recently used route from node i to the sink. The hop distance ℓ is obtained through a sink-generated broadcast performed at the start of network operations. This hop count can be updated in time, depending on the dynamics of the network topology. The energy estimates ϵ^i_ℓ are computed by node i rounding the outcome of the following recursive equation.

$$\epsilon^i_\ell = \begin{cases} e^i & \text{if } \ell = 1 \\ \frac{e^i + \epsilon^j_{\ell-1}}{2} & \text{if } \ell > 1 \end{cases} \tag{1}$$

where $e^i \in \{0, \ldots, k\}$ is node i currently available energy, discretized into a set of $k+1$ values, and $\epsilon^j_{\ell-1}$ is the energy estimate from the node j used as relay for node i last forwarding. The estimate $\epsilon^j_{\ell-1}$ has been sent from node j to node i during the last data exchange (see details below). Computing energy estimates is computationally efficient, as Equation (1) unfolds into the sum of the terms of the following finite series:

$$\epsilon^i_\ell = \frac{e^i}{2} + \frac{e^{j_{\ell-1}}}{4} + \frac{e^{j_{\ell-2}}}{8} + \ldots + \frac{e^{j_2}}{2^{\ell-1}} + \frac{e^{j_1}}{2^{\ell-1}} \leq k. \tag{2}$$

We note that the contribution to ϵ^i_ℓ of nodes increasingly away from node i is exponentially decreasing. This aims at lowering the effects of possibly outdated energy information from far away nodes on node i current estimate. Overall, the wake-up address of node i so obtained, implements ways to choose nodes that are closer to the sink (the w_ℓ part of the address) jointly with a method to forward that packet through routes with the highest residual energy ($w_{\epsilon^i_\ell}$ component).

Data packet forwarding. When a node i that is ℓ hops away from the sink has to forward a packet, it transmits a wake-up sequence $w = w_{\ell-1}w_{\epsilon_{\ell-1}}$ aimed at waking up nodes whose hop count is $\ell - 1$ and that are part of a route with the highest possible energy $\epsilon_{\ell-1}$. To this aim, node i sets $w_{\epsilon_{\ell-1}} = k$. Then, it turns on its own main radio and transmits a request to send the packet among those nodes that it just woke up, if any. This is accomplished by transmitting an `RTS` packet. A newly woken up node j that has correctly received the `RTS` packet, awaits a certain amount of time δ_{e^j} and then transmits a clear-to-send (`CTS`) packet, declaring that it is available to forward the packet. This time is inversely proportional to node j current residual energy e^j, to allow node i to select the most energetic relay. Time δ_{e^j} is added with an extra small random delay for avoiding that nodes with the same residual energy send `CTS` packets at the same time. Node i forwards the data packet to the sender of the first `CTS` packet that it receives, ignoring subsequent `CTS` packets. Data packets that are not acknowledged by the intended receiver are retransmitted up to a maximum number of times. If node i does not receive an acknowledgment for a data packet, the packet is discarded. Conversely, if no `CTS` packet has been received, node i broadcasts another wake-up sequence, this time trying to wake up those nodes whose energy level is $k - 1$. This process goes on until node i receives a `CTS` packet and a next hop relay j is found. After a predefined maximum number of retries is reached, if no relay is ever found, the packet is discarded. Diagrams illustrating the main operations of the senders and receivers are shown in Fig. 1 and Fig. 2.

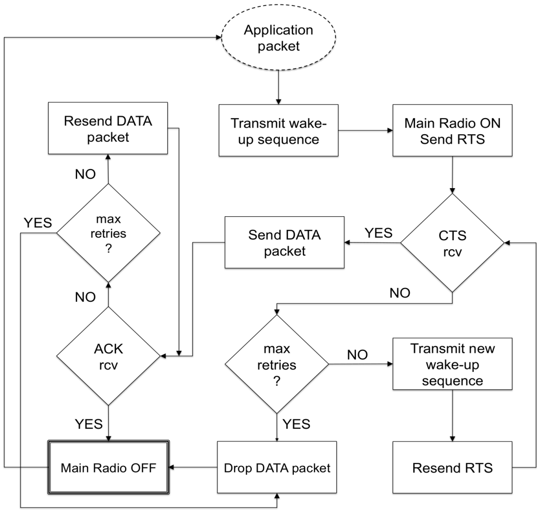


Fig. 1: Sender node i operations.

We conclude the description of GREENROUTES with two notes. 1. The cross layer forwarding used by our protocol provides us with a practically costless way of updating neighboring nodes with energy estimates. Particularly, relay j includes in the `CTS` header the most updated value of $\epsilon^j_{\ell-1}$, which node i will use to update its one wake-up address. 2. The relay selection process can be time consuming because of the repeated `RTS`-`CTS` exchanges needed to find a relay j. Aiming to reduce this delay, and to further improve protocol efficiency, we stipulate that node i stores the ID of its last successful relay j for a predefined amount of time. All packets that node i needs to transmit within this time will be transmitted directly to j, without any new relay selection phase. In this case, node i will wake up node j directly, i.e., by using its ID as wake-up sequence.

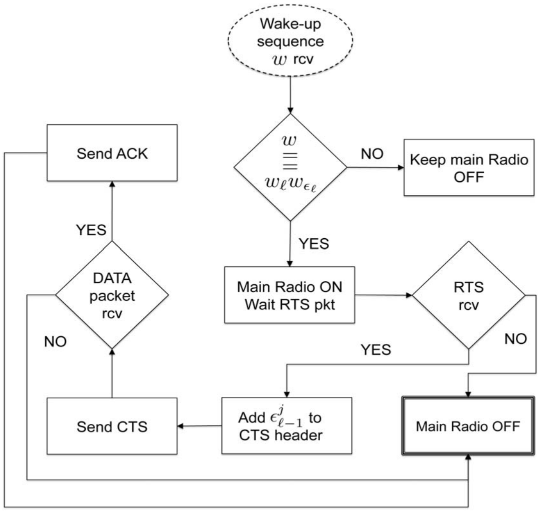


Fig. 2: Receiver node j operations.

IV. PERFORMANCE EVALUATION

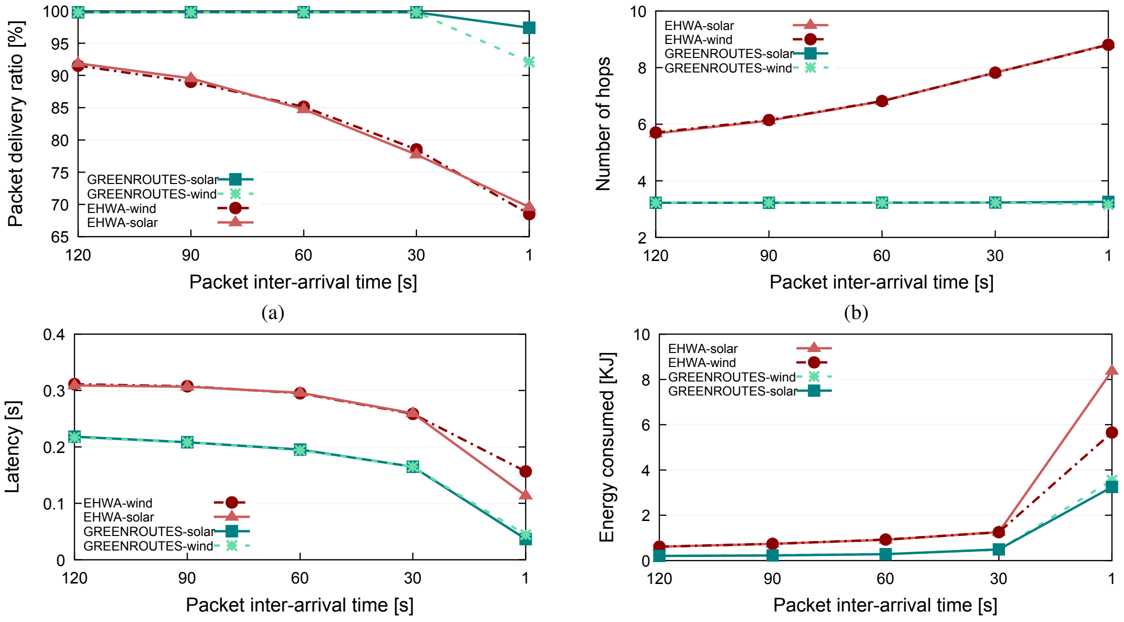
We compare the performance of GREENROUTES with that of EHWA [6], which we modify to use wake-up radios. In this case, nodes are woken up based on their own ID. Both protocols are implemented in the open-source simulator GreenCastalia [7], an extension of the Castalia simulator [12], which takes into consideration energy-related aspects of WSNs.

A. The EHWA routing protocol

EHWA is a DSR-based routing protocol for EH-WSNs that aims at minimizing the energy wastage of the network. Energy wastage occurs when the capacity of the storage device is maxed out, and further harvested energy is wasted. In EHWA nodes are characterized by their current residual energy, by a prediction of harvestable energy in the near future, and by an estimation of future energy consumption. Each route between a source and the sink is associated with a routing cost given by the sum of the energy consumed for transmission and of the network wastage from both on-path and off-path nodes. Nodes that belong to a route are on-path nodes, while the rest of the nodes are the off-path nodes. The sink node waits for a predefined time to receive a number of candidate routes and determines the one that yields the minimum energy wastage. As a result, longer routes are often preferred over shorter ones because of the higher number of nodes that uses the harvested energy instead of wasting it.

B. Simulation scenarios and setting

We consider connected networks where 64 nodes are randomly distributed as a 16×4 grid over an area of size $224 \times 56\text{m}^2$. The sink node is located at the bottom left corner



(a) (b)

(c) (d)

Fig. 3: Performance comparison of GreenRoutes and EHWA for increasing traffic.

of the deployment area. Network nodes harvest energy from the environment using the same external source, i.e., either via solar cells or via small wind turbines. We investigate the performance of the two protocols on both cases using harvesting traces obtained from the National Renewable Laboratory at Oak Ridge [13]. The harvested energy is stored in a supercapacitor with a maximum operating voltage of 2.3V and a capacitance of 50F [14]. Supercapacitors have the ability to retain energy throughout a longer life cycle, offering an advantage over batteries [15]. We assume that nodes are equipped with on-board Sensirion SHT1x sensors for temperature measurements. Sensing takes 171ms and consumes 3mW [16]. Sensing operation generation follows a Poisson process with inter-arrival time in the range of $[1, 120]$ sec. We consider scenarios where only 70% of the nodes, randomly chosen, perform sensor readings and generate data packets. Among these nodes a source node is randomly and uniformly chosen to generate a data packet. The rest of the nodes act only as relays. Sensor measurements are sent to the sink node as data packets whose size is set to 58B. The channel data rate is set to 250Kbps.

For the channel and radio models we use the default GreenCastalia settings. The main transceiver achieves a transmission range of 60m with a transmission power level of -2dBm. The average path loss between two nodes is estimated using the log-normal shadowing model used in [17]. Packet collisions are determined using an additive interference model, where transmissions from other nodes are calculated as interference by linearly adding their effect at the receiver. We model the wake-up radio based on the specifications of the wake-up prototype and the experimental measurements presented in [3]. Each wake-up sequence is transmitted at 1Kbps and has a size of 1B. In our simulations, the energy model is that of the MagoNode++ mote platform that supports energy harvesting and wake-up radio capabilities [18]. This platform features the ultra-low-power CC1101 transceiver from the Texas Instruments [19], that allows transmission of the wake-up sequences at $+10$dBm. The wake-up receiver (WUR) features a maximum sensitivity of -55dBm with a wake-up range of 45m. The power consumption of the WUR is set to 1.071μW.

C. Performance metrics

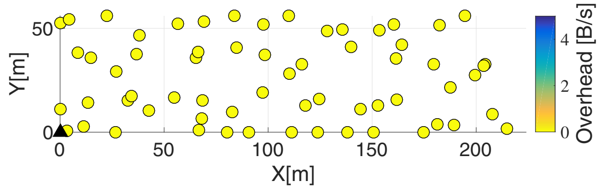
The effectiveness of our solution is evaluated by investigating the following performance metrics.

1) The packet delivery ratio, i.e., the fraction of generated data packets successfully delivered to the sink.
2) The length of a route to the sink (in hop-count).
3) The packet latency, i.e., the time required to successfully deliver a data packet to the sink.
4) The total energy consumed by the network nodes.

All metrics are evaluated vs. increasing traffic. The simulation time is set to 4 days. Results are obtained by averaging the outcome of a number of simulation runs that achieves a statistical confidence of 95% within a 5% precision.

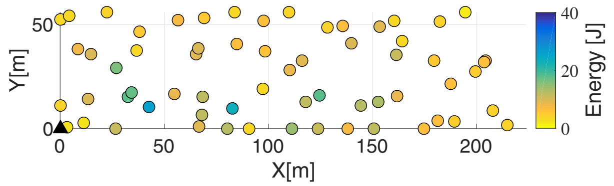
D. Performance results

1) Packet delivery ratio: The packet delivery ratio of the two protocols for different harvesting sources is shown in Fig. 3a. In all scenarios, GreenRoutes clearly outperforms EHWA and consistently attains a packet delivery ratio higher than 92%. At the lowest traffic, GreenRoutes delivers approximately 1.4 times more packets than EHWA, regardless of the energy harvesting source. We notice that the



(a) GreenRoutes: Overhead

(b) EHWA: Overhead



(c) GreenRoutes: Energy consumption

(d) EHWA: Energy consumption

Fig. 4: Per node overhead and energy consumption in networks with inter-arrival time of 30s and wind energy harvesting.

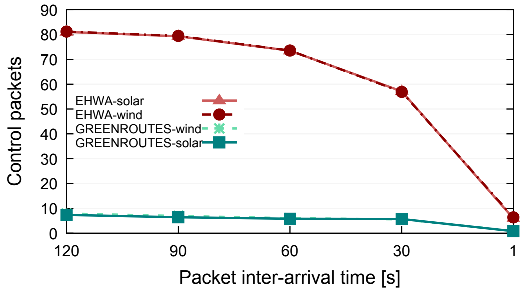


Fig. 5: Number of control packet transmissions normalized by the number of received packets.

performance of EHWA is decreasing with increasing traffic, while GreenRoutes exhibits a steady performance. The latter result depends on the clever selection of the next hop relay performed by GreenRoutes, which is lightweight and resource effective, waking up only those neighbors of a node that produce energy-efficient and shorter end-to-end routes.

At the highest traffic, GreenRoutes achieves 28% higher packet delivery ratio than that of EHWA in the case of solar energy harvesting. This is because EHWA suffers from a high amount of both control and data packet transmissions, which results in higher interference. In particular, EHWA requires up to 10 transmissions to successfully deliver a data packet to the sink, while it takes an average of less than 4 times to deliver a packet using GreenRoutes. This clearly suggests that EHWA is not as “light” as GreenRoutes when it comes to packet transmissions, and its route selection mechanism often results in longer routes.

2) *Route length:* Fig. 3b shows the average number of hops that a data packet traverses to reach the sink. Both protocols obtain similar performance for both energy harvesting sources. GreenRoutes delivers a data packet using an average number of three hops. EHWA requires at least 1.7 times more nodes to successfully deliver data packets to the sink, depending on the traffic. This is because GreenRoutes chooses the next hop relay by considering nodes with smaller hop counts (i.e., closer to the sink), taking jointly into account the total available energy along the most recently used route. In EHWA the sink node chooses a route solely based on the total energy wastage. As a result, longer routes are often preferred to shorter ones.

3) *End-to-end latency:* The average end-to-end packet latency is shown in Fig. 3c. Independently of traffic and energy harvesting source, EHWA experiences higher latency, which can be up to 3.5 times higher than those experienced by GreenRoutes. This is because of the longer routes that packets travel to the sink and also because of the route selection mechanism of EHWA, which the sink performs prior to data packet transmission. Particularly, the sink needs to wait for a predefined time to gather information from the nodes; it then needs some time to compute suitable routes, and it finally needs further time to send the route information back to the nodes. We observe that end-to-end latency decreases with increasing traffic for both protocols. This is because they both make use of cached information, namely, a next hop relay in the case of GreenRoutes, and full routes for EHWA. This eliminates a considerable amount of control packets, with beneficial effects on end-to-end latency, especially at high traffic (Fig. 5).

4) *Total energy consumption:* Fig. 3d depicts the average total energy consumption incurred by the two protocols. Despite its higher packet delivery ratio, GreenRoutes always consumes less energy than EHWA. This is mainly due to the higher number of control packets that EHWA sends. The performance gap is more noticeable at the highest traffic, where EHWA consumes 61% more energy than GreenRoutes (solar harvesting case). We observe that EHWA consumes higher levels of energy in the case of solar harvesting vs.

wind harvesting. This is consistent with the fact that packets take longer routes in scenarios with solar harvesting (Fig. 3b) due to higher energy wastage of routes. The performance of GREENROUTES is instead independent of the energy source, as its packets take shortest routes, and a limited number of control packets is needed to determine these routes. In general, GREENROUTES is more energy efficient in routing packets by jointly considering the distance of nodes from the sink, and, greedily, the residual energy along routes.

We further demonstrate the effectiveness of our approach by providing a quantitative assessment of the per node overhead and energy consumption of a sample topology (Fig. 4). The sink node is placed at the bottom left corner, depicted as a black triangle. Network nodes are depicted as circles. Our results concern nodes harvesting energy through a small wind turbine. Results about the overhead per time unit for GREENROUTES and EHWA are depicted through different colors in Fig. 4a and Fig. 4b. The darker the color the higher the overhead. We observe that EHWA nodes are colored in the shades of the darkest color, indicating higher levels of overhead, especially towards the center of the deployment area (Fig. 4b). This pattern is consistent with the behavior of a DSR-based protocol where nodes with a higher number of neighbors tend to receive and transmit a higher number of packets. Higher overhead leads to a higher energy consumption, as shown in Fig. 4c and Fig. 4d, where darker colors correspond to higher consumption. This affects the number of nodes that remain inactive for lack of energy, especially with high traffic. Specifically, at the highest traffic EHWA nodes remain inactive for a total of 52% of the simulation time. Nodes running GREENROUTES, instead, are inactive only for 7% of the time. In addition, GREENROUTES nodes are colored in lighter hues, showing lower overhead (Fig. 4a) and higher energy efficiency (Fig. 4c) throughout the network.

V. CONCLUSIONS

We presented GREENROUTES, a routing protocol for green networks that uses energy harvesting capabilities and wake-up radios with semantic addressing to efficiently select relays and routes with the best amount of residual energy. Through GreenCastalia-based simulations we compared the performance of GREENROUTES with that of EHWA, an energy wastage-aware routing protocol previously proposed. Results clearly show that GREENROUTES always outperforms EHWA with respect to every performance metric that we considered, regardless of traffic and of energy source considered, either sun or wind. In particular, GREENROUTES is able to deliver up to 40% more packets than EHWA to the sink, while consuming considerably less energy and delivering packets faster.

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