Enabling the Mobile IoT: Wake-up Unmanned Aerial Systems for Long-lived Data Collection

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***Abstract*—Networking and robotics are increasingly coming together to meet the requirements of applications that only advances in both fields can enable. This paper explores one of these joint applications, namely, using a robotic platform such as an Unmanned Aerial System (UAS) to wirelessly retrieve data produced by the devices of a sensor network. For energy conservation purposes devices operate according to a set duty cycle, or are endowed with wake-up radio transceivers allowing them to transmit and receive data only when needed. We define two simple UAS-aided data collection strategies depending on whether the devices use duty cycling or can be woken up by the visiting UAS. The performance of the two strategies is evaluated by using GreenCastalia, an open source simulator extended to model duty cycles, wake-up radio capabilities and the mobility of the UAS. We compare the two strategies with respect to the amount of data the UAS can collect in its visit, the energy consumption of the devices and the corresponding network lifetime. Our results show the key role of low-cost, low-energy consumption wake-up receivers in providing ways of collecting all data from the sensing devices while consuming a negligible fraction of the energy required to devices operating with a duty cycle. As a result, the lifetime of wake-up radio-based networks is orders of magnitude higher than that afforded to networks with duty cycling: Many decades vs. the very few years of networks with extremely low duty cycles.**

***Index Terms*—Unmanned Autonomous Systems (UASs), data collection, wake-up radio**

I. Introduction

Years of research on wireless networking, and especially on wireless sensor networks (WSNs), have brought advances and solutions allowing seamless interaction among humans, physical objects, sensors, actuators, and computing devices of all kinds and form factors. This has prompted all networking as we know it, and especially the Internet paradigm, to be extended to interconnect the physical world with unprecedented pervasiveness, creating what is now called the *Internet of Things* (IoT) [1], [2]. With new possibilities and opportunities, however, come new and important challenges, including providing devices with enough power to operate for long periods of time (e.g., years), tackling with, and even taking advantage of, device mobility, and designing energy aware and robust solutions for data collection at scale.

This work was supported in part by the Italian MIUR under grant "Dipartimenti di eccellenza 2018-2022" of the Department of Computer Science of the University of Rome "La Sapienza."

From the early days of resource-constrained wireless networking, solutions have been proposed to respond to these challenges. For instance, the issue of energy conservation for prolonged device and network lifetime has been addressed in many different ways. These include letting devices operate according to a set *duty cycle*, alternating between *asleep* and *awake* modes with energy consumption varying from μWatts to milliwatts, respectively [3]. More recently, to overcome the large delays of extreme duty cycling (e.g., staying awake for 5% of the device lifetime or less), low-cost, low-energy *wake-up radio* transceiver design has been proposed that allows devices to wake up selected neighboring nodes only when needed. In this way, a device consumes energy only when it needs to either transmit or receive useful information without having to wait for a neighboring device to wake up [4], [5]. Mobility has been effectively used to aid data collection in those scenarios where the need of simple design or scarcity of resources would not allow a device to support full-fledged operations and/or the implementation of a complete networking protocol stack. Instead of asking network devices to engage in channel access and in sophisticated data delivery schemes (e.g., multi-hop routing and transport protocols), a mobile device, usually resourceful and capable of complex communication and computation, is sent to visit the devices to collect their data and to deliver them to the user at a later time. Data delivery latency is traded off for simpler device design and for increased lifetime, which in turn corresponds to an overall longer network lifetime [6], [7]. Most works on mobility-aided data collection concern the design of routes with optimal length or visiting schedules that take into account device positioning and the constraints to the movements of the data collector, usually imposed by the specific application scenario (e.g., terrain characteristics or building layouts).

With the recent availability of *Unmanned Aerial Systems* (UASs), namely, airborne vehicles with relevant computation and communication capabilities, the performance of mobility-aided data collection has received a further push. Flying adds degrees of freedom to the data collector movements that enable new classes of applications, meeting new requirements such as lower data delivery times, independence from terrain characteristics, and coverage of larger network deployment areas (see [8] and Section IV).

This paper aims at contributing to the exploration of the use of UASs for data collection in network of devices operating either according to a set duty cycle or using wake-up radio transceivers. Particularly, we are concerned with a network scenario where a UAS visits sensing devices statically deployed in a given area to collect data of different nature (e.g., temperature, humidity, or visual data). We define two simple UAS-aided data collection strategies depending on whether the devices operate with duty cycling or can be woken up by the visiting UAS. Both strategies are implemented in GreenCastalia [9], the open source extension of the simulator Castalia for WSNs [10] extended to model duty cycling and wake-up radio transceivers realistically [11]. We further extend the mobility manager module of GreenCastalia to support the mobility of the UAS. Differently from the few works considering "wake-up UASs" for data collection, which are mostly concerned with communication range [12] and in determining optimal visiting routes [13], we compare the two strategies with respect to the amount of data the UAS can collect in its visit, the energy consumption of the devices and the corresponding network lifetime. Our results show the key role of low-cost, low-energy consumption wake-up receivers in providing ways of collecting all data from the sensing devices while consuming a negligible fraction of the energy required to devices operating with a duty cycle, even a very low one (e.g., 1%). As a result, the lifetime of wake-up radio-based networks amounts to several decades, which is orders of magnitude higher than that afforded to networks with duty cycling (a mere 0.3 or 1.7 years with duty cycles of 5 or 1%, respectively). The main reasons of these results stem from the advantages introduced by the last-generation wake-up radio technology, which transforms a device into a multi-radio system to all effects and purposes. This not only voids the detrimental effects of idle energy consumption but also provides an out-of-band way of managing control and resources, thus decreasing interference and related overhead. Equally important, we show that the relevance of our results is irrespective of the specifics of the wake-up radio-based data collection strategy, e.g., of how optimized is the route followed by the UAS or of the UAS characteristics. This clearly makes "wake-up UASs" the new enablers of the future mobile IoT.

The rest of the paper is organized as follows. In Section II we describe the data collection scenario considered in this paper along with the wake-up radio-enabled and the duty cycle-based data collection strategies. The comparative performance evaluation of the two strategies is reported in Section III. Section IV concerns a review of works pertinent to our research. Finally, Section V concludes the paper.

II. Scenario and Data Collection Strategies

In this section we illustrate the general scenario for data collection considered in the paper (Section II-A). We then provide the description of the two data collection strategies compared in our investigation, which consider devices operating according to a pre-defined duty cycle (Section II-B), and devices with wake-up radio capabilities (Section II-C).

A. Data Collection Scenario

We consider a set of n devices that are capable of sensing multiple physical phenomena (e.g., temperature, humidity, etc.). These devices (also called nodes in the following) are statically scattered (randomly) in a deployment area of known dimensions $(X \times Y)\mathrm{m}^2$. Each node can also communicate through an on-board wirelessly technology (radio) capable of transferring the sensed data up to r_m meters away and at a data rate of $d_m$bps. Sensing and data communications are powered by energy from an energy storage source available at each device (e.g., battery or supercapacitor). In this work we do not consider rechargeable energy sources or any form of energy harvesting available to the devices. As such, once a device has depleted its energy, it "dies," i.e., it is no longer capable of performing sensing or communication functions.

For the purpose of data collection, nodes are periodically visited by one Unmanned Aerial System (UAS) that flies at a fixed height of Zm above the deployment area. The UAS takes τ seconds to complete the visit to all devices in the deployment area. We stipulate that this time is inferior to the UAS' *flying autonomy*, namely, to the lifetime afforded to the UAS by its own energy source.[1] The UAS scans the deployment area according to a pre-determined pattern (UAS route). Particularly, the UAS stops at pre-selected *collection points* on its route for s seconds. There, it hovers to collect sensed data from the devices within its radio communication range r_m. The collection points are selected in such a way that all devices are capable of providing the UAS with their data. Once all devices have been visited, the UAS exits the area and delivers the collected data to their intended user.

Fig. 1 depicts the general data collection scenario considered in this paper. The route followed by the UAS is depicted on top. The sensing devices are scattered throughout the bottom (red dots).

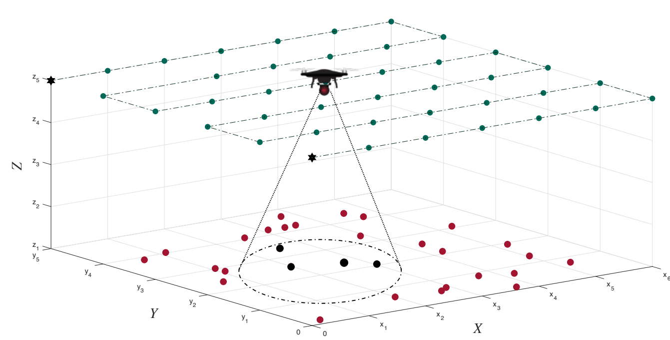

Fig. 1: A general data collection scenarios.

In this specific figure the UAS follows a *lawn mower* pattern, where the whole deployment area is flied upon back and forth according to parallel straight lines (other patterns

[1] In this paper we consider deployment areas that can be wholly visited by a single UAS within its flying autonomy. The case of deployment areas whose extent exceeds the possibility of being visited by a single UAS can be dealt with by using multiple UASs, or by sending the same UAS to different areas after appropriate re-charging times.

are also possible). The two stars indicate the entry and the exit points of the UAS to the area. The collection points are indicated by darker circles along the UAS route. The figure shows the UAS hovering at a collection point. The cone beneath the UAS indicates the extent of the UAS wireless coverage, namely, the ground area whose devices are capable of receiving transmission from the UAS (black dots in the figure). The wireless coverage area depends on the specific wireless technology used by the devices and the UAS to communicate.

B. Duty Cycle-based Data Collection

For this data collection strategy we consider a scenario where each device that is not transmitting or receiving packets operates according to a pre-defined duty cycle. Particularly, the device radio stays off for a set time t_{off} (consuming power in the order of μW), after which it is turned on for a set time t_{on} (consuming power in the order of mW). It is then turned off again for t_{off} seconds, and so on. The duty cycle of each node is determined as the percentage of the radio "on time" with respect to the simulation time.

Strategy: When the UAS reaches a collection point it broadcasts a *request packet* (req packet, for short) containing a sequence of bits encoding the specific measurement it is currently interested in. For instance, for collecting data concerning "temperature" it would broadcast a req packet with sequence 1010 as payload; for "humidity" it would broadcast the payload 1101, and for "luminosity" the payload would be 1100. Each req packet has an overall length of p_r bits. To increase the chances for a device to receive a req packet, the UAS will broadcast it a number $b_r > 0$ of times during the s seconds it stays at each collection point. Any device that is capable of receiving a req packet, namely, every device whose radio is on and that can provide the requested measurement, performs the measurement, crafts the corresponding data packet and transmits it to the UAS. Every data packet has an overall length of p_d bits. In order to avoid overlapping arrival of packets from multiple devices at the UAS (creating interference, namely, voiding the reception of all colliding packets), each source device d will transmit its packet after a short delay δ_d selected randomly and uniformly in the interval $0 \leq \delta_d \leq \delta_{max}$.

For this scenario, the cone under the UAS in Fig. 1, namely, its wireless coverage, would concern the devices that are reachable by the UAS using its main radio, namely, all devices whose distance from the UAS is $\leq r_m$.

C. Wake-up Radio-enabled Data Collection

In this scenario, all devices as well as the UAS are equipped with two wireless transceivers. One is the *main radio*, which is used to transmit data packets carrying the sensed information. This radio consumes energy in the order of mW, even when idle. For this reason, it is usually turned off (*sleep mode*) unless needed for transmission or reception of packets. When off the main radio consumes in the order of μW, namely, three orders of magnitude less than when it is on. The other transceiver is the *wake-up radio*, which is used to wake-up (i.e., turn on) the main radio of those devices that receive a wake-up signal. This radio consumes mW for transmitting bits, as the main radio. For this reason, the transmitter is kept on only when it is needed for transmission, otherwise it is turned off (consuming nothing). Wake-up receivers, instead, consume only μWatts for receiving bits and also when idle. The wake-up receiver is always kept on. Wake-up radio transmitters broadcast a *wake-up sequence* (or address) w that is p_w bit long. The sequence is received by all devices within the wake-up radio range r_w. The wake-up radio channel has a data rate of $d_w$bps. Only devices that have sequence w set as one of their wake-up addresses turn on their main radio; all other nodes remain with the main radio in sleep mode. The architecture of a wake-up radio-enabled device is depicted in Fig. 2.

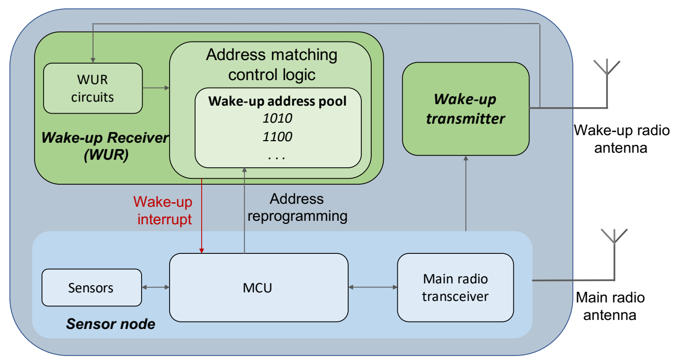

Fig. 2: The architecture of a wake-up radio-capable device.

The *sensor node*, in the bottom of the figure, implements typical sensing device functions: Sensing (through its sensors), computing and application/protocol functions (MCU), and communications (transceiver of the main radio, with its own antenna system). The *wake-up transmitter* (top right) takes care of transmitting wake-up sequences as dictated by the specific application (run on the sensor node). It uses a dedicated wake-up antenna system. Finally, the *wake-up receiver* (WUR) is comprised of two main components (top left of Fig. 2). The *WUR circuits* that receive the signal from the wake-up antenna system and decode it into a wake-up sequence,[2] and the *address matching control logic* that is in charge of reprogramming the wake-up addresses (as mandated by the application/MCU) and of matching the sequence received from the WUR circuits to those currently in the wake-up address pool. If the sequence just received is one of the current wake-up addresses, the WUR wakes up the sensor node (sensors and main radio) through a wake-up interrupt. Otherwise, the

[2] In this specific figure the antenna is shared with the wake-up transmitter. Many actual wake-up radio designs feature two separate antennas for the transmitter and for the receiver [11].

WUR discards the sequence and the device keeps sleeping.[3]

In this paper each device sets its wake-up addresses according to the sensing measurements it can currently provide. For instance, if the address for "temperature" is the sequence $w_t = 1010$, that for "humidity" is $w_h = 1101$ and that for "luminosity" is $w_l = 1100$, and if device d can currently provide only measurements for temperature and luminosity, then d will set its wake-up address to 1010 and 1100. This could change in time, in that if at a later time device d will be only able to provide measurements of luminosity it will update its wake-up address pool to contain only the sequence 1100.

Strategy: When the UAS reaches a collection point it transmits the wake-up sequence w corresponding to that of the measurement it is currently interested in. The sequence is re-transmitted a maximum of $b_w > 0$ times increasing the probability that all devices in range wake up. The devices that receive the sequence w will wake up their main radio only if w is in their wake-up address pool. They will stay dormant if sequence w is not among their selected wake-up address. Once a device is up, it will take a measurement, craft the corresponding data packet and transmit it to the UAS using its main radio. As in the case of the duty cycle-based strategy, in order to avoid interference of data packets at the UAS, each source device d will transmit its packet after a short delay δ_d, selected randomly and uniformly in the interval $0 \leq \delta_d \leq \delta_{max}$.

For this scenario, the cone under the UAS in Fig. 1 would concern the devices (indicated by black dots) that are reachable by the UAS using its wake-up radio radio, namely, all devices whose distance from the UAS is $\leq r_w$. As it is usually $r_w \ll r_m$, and as the main radio technology is much more reliable than that of the wake-up radio, every node that is woken up by the UAS should be able to send a data packet to the UAS.

III. Experimental Evaluation

We evaluate the performance of the two data collection strategies by simulations. Both strategies have been implemented in the open-source simulator GreenCastalia [9], an extension of the OMNeT++ based simulator Castalia [10] that models wireless sensor devices in details. In the following we describe the simulation settings for both scenarios (Section III-A), the metrics investigated for our performance comparison (Section III-B), and the simulation results (Section III-C).

A. Simulation Settings

Settings for the general scenario. We consider a number $n = 150$ of devices that are deployed randomly and uniformly in a rectangular area of dimensions $X = 490$m and $Y = 400$m. Devices—energy model and architecture—are modeled according to the specification of the MagoNode++, a low-cost, low-energy mote designed for wireless sensor networking and IoT pervasive applications [14]. Channel and radio models are set based on the default GreenCastalia settings. The channel data rate d_m is set to 250Kbps. The transmission power of the main transceiver has been set to achieve energy conservation at -2dBm, leading to a transmission range r_m of 60m. The lognormal shadowing model is used to estimate the average path loss between points in the space with respect to where a device and the UAS reside [15]. Possible packet collisions at the UAS are determined using an additive interference model, by linearly summing-up at the receiver the effect of multiple signals simultaneously sent. In our experiments we assume that each device can perform temperature measurements, producing a corresponding data packet of 62B, inclusive of the application payload (temperature value), and headers added by lower layers (simple CSMA MAC and physical layer). The device spends 3mW to produce the requested measurement. Each device is powered by two 1.5V AA alkaline batteries whose capacity is 2500mAh.

We extended the mobility manager module of GreenCastalia to support the specific mobility of the UAS. The UAS follows a lawn mower pattern to scan the deployment area in order to collect sensing data from the devices (Fig. 1). It flies at a fixed height Z set to 20m above the deployment area for $\tau = 1200$s (which we also set as the total simulation time). We found this flying time to be compatible with the flying autonomy of typical commercial UASs that can carry a payload equivalent in weight to that of a MagoNode++ with a wake-up radio system as the one modeled in this paper (about .5kg). The distance between successive collection points on the UAS route is set to 40m. The UAS flies at the speed of 20m/s between collection points. Once at a collection point, it hovers there for $s = 6$s for collecting data.

Settings for the duty cycle-based scenario. Devices go to sleep and wake up according to independent awake-asleep schedules with a fixed duty cycle $c \in \{1, 5, 10, 100\}\%$. Once the UAS is at a collection point it broadcasts a req packet p that is $p_r = 6$B long. The packet carries the request for a specific measurement (temperature, in our experiments). The broadcast of packet p is repeated $b_r = 10$ times, equally spaced within the $s = 6$s of permanence of the UAS at the collection point. Devices that receive a packet p reply with a data packet after a time δ selected randomly in the interval $[0, \delta_{max} = 500]$ms.

Settings for the wake-up radio-based scenario. We extend GreenCastalia to model a real wake-up radio-based system. Particularly, the model of the MagoNode++ mote is extended to support an ultra-low-power receiver and a wake-up transmitter capable of sending wake-up sequences of the kind used by our collection strategy (Section II-C). The wake-up radio system is modeled based on the specifications of a wake-up radio receiver prototype of our design that we tested and characterized [11]. Wake-up sequences are sent at $+10$dBm using the low-power CC1101 transceiver from Texas Instruments [16]. They are 4 bits long, and are transmitted at 5Kbps. The power consumption of the receiver is 1.071μW.

[3] We notice that for the specific application scenarios considered in this paper, the architecture of a device with full-fledged wake-up radio capabilities shown in Fig. 2 may be unnecessary. In fact, devices would only need the wake-up receiver, which would simplify design and decrease the overall device layout and costs. Similarly, the UAS would only need a wake-up transmitter.

Its sensitivity is -55dBm, leading to a maximum wake-up range r_w of 25m. These values are consistent with those from a recent experimental measurement campaign [17]. According to this campaign, with this sensitivity and at a distance of 20m between transmitter and receiver, the average probability of receiving wake-up sequences correctly is 90%. In our experiments we use this probability to determine whether a device wakes up or not once a wake-up sequence has been transmitted. To increase the chance that every device is woken up we set the number of times b_w that a wake-up sequence w is sent at a collection point to 5.

Our simulation model also considers the power consumption of the integrated ultra-low power microcontroller (MCU) used to perform wake-up addressing, which consumes 0.036μW and 54μW in idle and active states, respectively.

The simulation parameters are summarized in Table I.

TABLE I: Simulation parameters.

Symbol	*Definition*	*Value*
n	Number of devices	150
X, Y	Deployment area size (ground)	490×400m^2
Z	UAS flying height	20m
τ	UAS total visit time	1200s
-	UAS route	"lawn mower"
-	Distance between collection points	40m
s	Time at each collection point	6s
r_m	Main radio range	60m
d_m	Main radio data rate	250Kbps
c	Duty cycle	$\{1, 5, 10, 100\}$%
b_r	Number of req packets sent	10
p_r	Length of req packets	6B
p_d	Length of data packets	62B
r_w	Wake-up radio range	25m
d_w	Wake-up radio data rate	5Kbps
p_w	Length of wake-up sequences	4b
b_w	Number of wake-up sequences sent	5
-	Sensing device battery	2×1.5V alkaline
-	Battery capacity	2500mAh
-	Sensing power consumption	3mW
-	WUR power consumption	1.071μW
-	MCU power consumption (idle)	0.036μW
-	MCU power consumption (active)	54μW
δ_{max}	Maximum packet delay time	500ms

B. Investigated Metrics

The performance of the two data collection strategies have been compared with respect to the following metrics.

1) The *number of collected packets*, i.e., the total number of data packet collected by the UAS by the end of its visit.
2) The *total energy consumption*, defined as the sum of the energy spent by each device throughout the simulation time.
3) The *network lifetime*, defined as the time from the start of network operations until the first device runs out of energy.[4] (We stipulate that devices are continuously visited by an UAS, namely, that once one UAS has finished a visit to the device, another one follows for a new data collection.)

Results are shown for the duty cycle-based collection strategy varying the duration of duty cycle and for the wake-up radio-based strategy.

All results have been obtained by averaging the outcomes of a number of simulation runs sufficient to obtain 95% confidence with 5% precision.

C. Simulation Results

1) Number of collected packets: Fig. 3 depicts the average number of packets collected by the UAS using the two forwarding strategies.

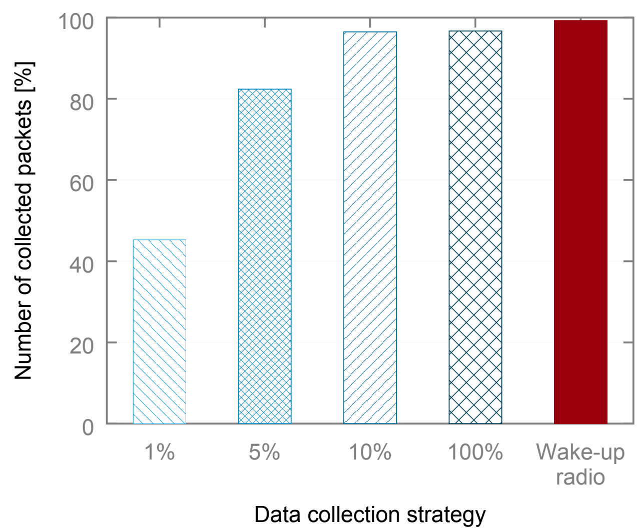

Fig. 3: Total number of collected packets.

Almost all packets transmitted by devices with wake-up radio are successfully received by the UAS. Particularly, the UAS manages to collect more than 99% of the temperature measurements. We notice that while all devices send a sensed measurement, few of the packets, i.e., less than 1%, are lost. This is due to collisions of sent packets at the UAS. This also means that all nodes within the range of the UAS correctly wake up. The "full duty cycle" strategy ($c = 100\%$) also obtains a high percentage of collected packets. However, even though all devices are always awake during the UAS visit, the UAS collects 2.6% less packets than those gathered by a UAS with a wake-up radio. This is because of collisions of data packets at the UAS. Lowering the duty cycle value, as expected, exhibits inferior performance because it is more difficult for the UAS to find nodes that are awake. In particular, when $c = 10\%$ the performance further decreases by 2.8%.

[4] This definition is consistent with that of many works concerning the lifetime of wireless sensor and IoT networks. Although the network may still serve the purpose of the application despite some of its devices are dead, this conservative definition provides an informative lower bound on the network performance for this metric [18].

When devices operate at a even lower duty cycle, namely, $c = 5\%$, the performance of the network becomes more sensitive to the time a node is awake. In this case, only 82.36% of the devices manage to successfully transmit their data to the UAS. This is mainly due to not being able to find a node that is awake, which results in a higher number of packets not generated/transmitted. The number of collected packets decreases to 45% for the smallest value of the duty cycle ($c = 1\%$). This value corresponds to more than half of the packet collected by an UAS with a wake-up.

2) Total energy consumption: Fig. 4 shows the total energy consumed by the network.

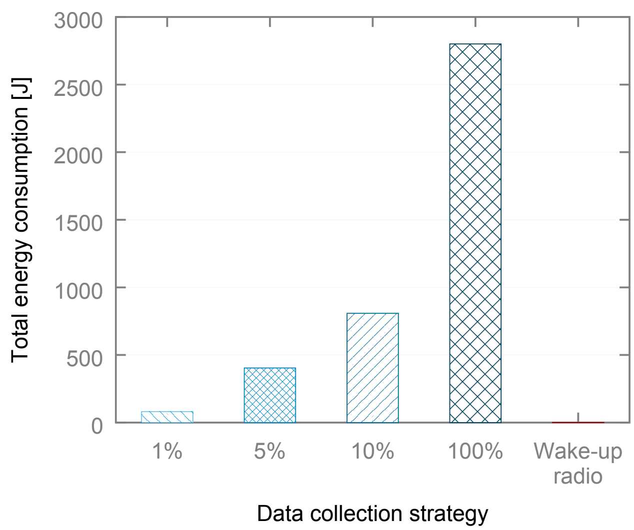

Fig. 4: Total energy consumption.

The wake-up radio-based data collection strategy shows remarkable performance, reducing the energy consumption of the network by approximately three orders of magnitude with respect to the strategy with 100% duty cycle. (Its energy consumption—1J—is so low that is barely visible in the figure). Nodes operating at a moderate/low duty cycle, i.e., 10% and 5%, still consume noticeable amounts of energy, showing 787 and 393 times higher energy consumption than that of the wake-up radio-based strategy, respectively. Even when nodes operate at very low duty cycle (1%), devices with a wake-up radio induce an average total energy consumption that is 78 times lower. As expected, the culprit is in the fact that duty cycle-based strategies do not eliminate idle listening (on the main radio) as wake-up radio-based strategies do. It is the ability of devices to wake up "on-demand" and only when needed that allows them to consume as little energy as possible.

3) Network lifetime: Expected network lifetime is shown in Fig. 5 (in days; logarithmic scale).

The remarkably low energy consumption of the wake-up radio-based data collection strategy allows to achieve expected network lifetime of *several decades*.[5] In comparison, a network allowing devices to be always awake ($c = 100\%$) would last only for a bit more than *one week*. When devices are awake for 10%, 5%, and 1% of the UAS visit time the lifetime of the network is expected to last 65, 131, and 656 days, respectively. Therefore, the network lifetime is constrained by the time nodes remain awake due to the need of being able to receive request packets and transmit their own data, which results to higher energy consumption. Our results show the key role of low-cost, low-energy consumption, small form factor wake-up receivers in providing impressively long lasting IoT and sensing systems. In fact, our investigation shows that endowing devices with wake-up radios is enough for obtaining network lifetimes that exceed the lifetime of common energy sources for network devices (e.g., batteries and even last-generation supercapacitors [19]). Equally important, these results do not depend on the specifics of the wake-up radio-based data collection strategy, e.g., on how optimized is the route followed by the UAS, etc. They are obtained by a very generic UAS following a very standard flying pattern.

[5] While these results are representative of the network lifetime in the long run, actual values can vary depending on the energy source considered.

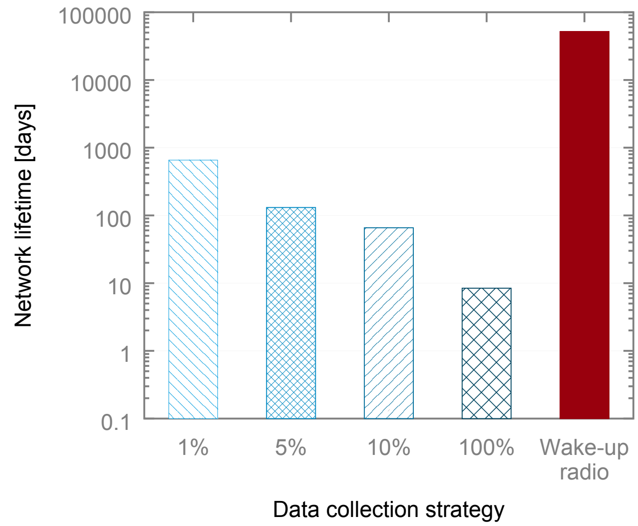

Fig. 5: Network lifetime.

IV. Related work

The idea of leveraging the mobility of resource-rich devices to gather data from resource-constrained sensors—a process often called *data muling*—has been explored quite extensively since research has started on wireless sensor networks [20], [21], [22], [6]. The most recent solutions using this kind of data collection methods concern IoT scenarios like smart grids (where cell phones are used as mules [23], [24]) and smart cities (with urban vehicles as data mules [25]). The reader is referred to the survey by Gu et al. for details and further references [7]. Most data muling solutions, however, concern terrestrial scenarios where sensing devices are statically deployed in a given area and are visited by one or more mobile data collectors also proceeding on terrestrial routes.

Recent advances in (and the lower costs of) robotic systems and aerial vehicles have made possible to use UASs for aiding and improving many key networking functions and to enable new applications [26], [27]. Data collection with UASs used as mules, as explored in this paper, is one of the areas that has received due attention [8], [28], [29], [30], [31], [32], [33], [34], [35]. In this section we review these previous solutions.

Wang et al. propose a framework for data collection with UASs that includes network deployment, device localization, swift path planning for the UAS, and of course data retrieval [8]. Differently from our setting, this work is primarily focused on the investigation of the time it takes for the UAS to visit the sensing devices, and on the amount of data that can be collected in that time.

The work by Mazayev et al. concerns UAS-based data collection for applications with data delivery timing constraints [28]. An optimal mathematical formulation and a heuristic algorithm are presented to determine an efficient set of routes for the UAS to collect sensor data from devices at known locations and to deliver them timely to the (remote) user. The focus of this work is on UAS route determination for timely data collection, rather than on energy conserving collection strategies, as we do here.

Bagula et al. are interested in scenarios where teams of UASs are sent to certain areas to be covered for data collection or monitoring purposes [29]. Similarly, Tuyishmire et al. are concerned with teams of UASs for cooperative data collection and the timely delivery of data to designated base stations [30]. The focus of both works is on providing optimal and heuristic algorithms for path planning and task assignment to the UASs aimed at minimizing the cost of the deployment of UASs, rather than on data collection and related performance metrics.

The work by Gong et al. considers the very specific scenario where a UAS collects data from devices placed on a straight line [31]. The objective is to minimize the UAS total flight time while allowing each sensor to successfully upload a certain amount of data under given energy constraints. The aim of the work is that of jointly optimizing the UAS speed and the energy consumption of the sensing devices, with no emphasis on network lifetime.

Zhan et al. consider a WSN scenario with devices alternating between asleep and awake mode (duty cycling) that are visited by a UAS for data collection. A mixed-integer nonconvex optimization problem is formulated for determining device wake-up schedules and UAS route that minimize the energy consumption of all devices while ensuring that the required amount of data is collected. A heuristic solution is provided whose effectiveness in producing energy savings with respect to baseline solutions is shown via numerical results. No realistic modeling of UAS and devices is provided in the work, or a quantitative measure of network lifetime.

The work by Zhong et al. concerns optimal solution and heuristic to the problem of finding routes to dispatch multiple UASs to users that are isolated after a dire event (e.g., a natural disaster) [33]. A "mission planning problem" is formulated as an integer linear program, and solved optimally, to obtain the minimum mission time for the UAS to visit the area of interest where the stranded users are. A near-optimal heuristic is then proposed, which is compared to the optimal algorithm via MATLAB-based simulations with respect to the total mission time, namely, the time it takes to all UASs to visit the area. As such, the focus of the work is not on data collection but it is rather on UAS visit times.

Ebrahimi et al. propose the use of a UAS to collect data in dense WSNs whose devices are partitioned into clusters, each with a designated clusterhead device [34]. The idea is that of smartly reducing the data to be gathered by aggregating them at the clusterheads that are then visited by the UAS. Their solution comprises clustering the sensors, constructing an optimized forwarding tree per cluster, and collecting the data from selected CH nodes following shortest UAS routes. Simulations results are shown for metrics such as total energy consumption, UAS route length and execution time, with no quantitative measure of network lifetime or packet delivered.

A similar scenario is considered in the work by Tuyishmire et al., where a clustering scheme is proposed that optimizes not only the energy usage of the sensing devices, but also the energy used by the UAS [35]. The computation of the number of optimal clusters is inspired by the k-means clustering algorithm used as a network design technique for hybrid UAS/terrestrial networks. The corresponding clustering and UAS visit algorithms are evaluated by simulations with respect to the general cost of deploying the UAS.

All these papers concern UAS-assisted wireless sensor and IoT networking. None of them, however, considers leveraging the tremendous energy savings that can be obtained by using wake-up radios. Works for data collection via UASs that use wake-up radios for longer network lifetime are uncharted territory. Chen et al. advocate the use of a wake-up radio on UASs for superior energy conservation [12]. This work, however, aims at investigating the wake-up range and energy costs of RF-based and infrared (IR)-based wake-up radios for communications to/from a UAS and a sensing device, without being concerned with data collection from multiple devices or with network lifetime. The wake-up range of their proposed system appears to be limited to a few meters ($<$ 7m for both RF and IR-based wake-up), which is well below the system used for the model in our work ($<$ 25m [17]).

To the best of our knowledge the use of a "wake-up UAS" used as a mobile data collector has only been explored in the work by Yomo et al. [13]. This work focuses on a problem that is quite different from the one investigated in our paper. It concerns determining the best route for a UAS with a wake-up transmitter to collect data from devices with wake-up receivers so that the energy consumption of both UAS and of the sensing devices is minimized. This allows the UAS to fly longer (and collect more data) and the devices to last longer. A heuristic is proposed for computing the UAS route through the sensing devices that is benchmarked to that of optimal solutions via simulations and a small testbed. The work presents no quantitative comparison between the use of duty cycling vs. that of wake-up radios, no study on the energy consumption of the devices, or on their lifetime, as we do in our paper.

V. Conclusions

We present ways for a UAS to visit and collect data from the devices of a WSN. We define two collection strategies depending on whether the devices use duty cycling or can be woken up by the visiting UAS. Through GreenCastalia-based simulations we compare the performance of the two strategies over metrics such as the amount of data the UAS can collect in its visit, the energy consumption of the devices and the network lifetime. Our results show that low-cost, low-energy consumption wake-up receivers are highly effective in enabling the collection of all data from the sensing devices at a fraction of the energy cost required to devices operating with a duty cycle. As a result, the lifetime of wake-up radio-based networks is orders of magnitude higher than that of networks whose nodes duty cycle: Very many decades as opposed to the very few years of networks with extremely low duty cycles (0.3 or 1.7 years with duty cycles of 5 or 1%, respectively).

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