Experimental Evaluation of Wake-up Radio Ranges for UAV-assisted Mobile Data Collection

Abhimanyu Venkatraman Sheshashayee
Institute for the Wireless Internet of Things
Northeastern University
Boston, MA, U.S.A.
E-mail: sheshashayee.a@northeastern.edu

John Buczek
Institute for the Wireless Internet of Things
Northeastern University
Boston, MA, U.S.A.
E-mail: buczek.j@northeastern.edu

Chiara Petrioli
Department of Computer, Control
and Management Engineering
University of Rome "La Sapienza"
Rome, Italy
E-mail: petrioli@diag.uniroma1.it

Stefano Basagni
Institute for the Wireless Internet of Things
Northeastern University
Boston, MA, U.S.A.
E-mail: s.basagni@northeastern.edu

***Abstract*—This paper investigates the physical performance of mobile data collection systems comprising Unmanned Aerial Vehicles (UAVs) in conjunction with Wake-up Radio (WuR) technology to minimize the energy consumption of data exchange with Wireless Sensor Network (WSN) nodes. We setup data collection experiments using a quad-rotor drone as the UAV and WuR-enabled motes as the communication nodes. Our experiments are calibrated using tests that measure flight time, communication range and the performance of data collection using WuR compared with that of data collection when the mote duty cycles. We confirm that collection using duty cycling consumes far more power and achieves lower reliability than collection using WuR technology. In our ranging experiments we observe that while the Mobile Data Collector (MDC) is flying at an altitude of approximately 5 m, reliability decreases monotonically with horizontal distance, averaging at 75.4% of all data packets being successfully collected, while latency averages at 27 ms. At an altitude of 10 m, reliability drops considerably to an average of 14.33%, while latency increases with horizontal distance, averaging at 71.16 ms.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are typically comprised of battery-powered *motes* that can be deployed in very many different kinds of scenarios [1]. These networks are used for a variety of sensing and monitoring tasks. In the years, they have favored the scientific and commercial success of new technologies and applications, including many that are now at the core of the *Internet of Things* [2]. Data reporting from the sensor motes to the WSN collection points, namely, the *sinks*, happens wirelessly. This allows the deployment of the motes in possibly remote or hard accessible areas, enabling a vast variety of applications otherwise too difficult to realize. The devices at the core of WSN face major challenges, the first of which is undoubtedly energy consumption: motes have a limited battery supply. This is a major impairment, especially when motes are deployed in situation that makes battery replenishment or substitution prohibitive. Additionally, interference due to terrain or other factors can result in limited connectivity between motes, which sometimes makes data routing to sink problematic, inefficient, or even impossible. This can make it difficult to collect data from motes in a WSN.

An approach to attenuating the effects of these limitations is that of using *mobile data collection* whereby the sink is mounted on a vehicle to form a *Mobile Data Collector* (MDC). This MDC traverses the region in which the WSN has been deployed and collects data from each *Sensor Node* (SN) on the ground. If the MDC is sufficiently mobile, such as an *Unmanned Aerial Vehicle* (UAV) [3], then collecting data from remote motes becomes significantly less difficult. While the MDC locomotor can incur a significant energy cost, it can be periodically replenished at a charging station. Thus, as long as the MDC can complete a data collection cycle before it depletes its power reserves, it will effectively be able to operate indefinitely. If resources allows, multiple MDC could also be used alternately, thus ensuring continuous data collection and preventing data losses at the mote. Mobile data collection also produces remarkable energy savings, in that even if multi-hop routes could be found from a mote to the sink, it frees the motes from running energy-hungry routing protocols. The effectiveness of this data collection method has been demonstrated by many a solution, abundantly surveyed [4], [5], [6].

The lifetime of WSNs with MDCs is however still limited by the problem of *idle energy consumption* of the radio of the sensor nodes. When the MDC is not passing by to collect data, their radios unnecessarily consume power. The mote can partially alleviate this problem with *duty cycling*, wherein the radio is left turned off (*asleep*) for the majority of the time, and only turned on (*awake*) periodically [7]. However, if the MDC passes by a mote while it is dormant, it will be unable to collect the data, resulting in significant delays and even data loss. A solution for this is provided by *Wake-*

up Radio (WuR) technology [8]. Here, an ultra-low-power auxiliary radio is appended to the devices. By default, the motes turn off their main radio (*asleep*). When two motes need to communicate, the sender signals the receiver with a *Wake-up Sequence* (WuS). Then, both motes turn on their main radios (*awake*), and exchange data packets. After a timeout, the motes return to their dormant state. The effectiveness of WuR-based data collection, whether aided by an MDC or not, has been demonstrated widely. The best performance results were obtained through WuR with WuS that implement forms of context-based (*semantic*) awakenings [9], [10], [11], [12].

In this investigation, we examine the performance of mobile data collection using WuR technology and a UAV-MDC. We conduct physical mobile data collection experiments using a quad-rotor drone and WuR-enabled wireless sensor motes. Our experiments are divided into *calibrations* and *ranging*. Calibrations experiments are aimed at measuring certain preliminaries of mobile data collection, including: maximum flight time, maximum effective range for data exchange, and a comparison of data collection using WuRs and duty cycling. We find that reliability for both WuR-based data collection and 100% duty cycled data collection are nearly identical, with approximately 90% of all data packets successfully collected.[1] Meanwhile, energy consumption of WuR-based collection is approximately 2.7% that of 100% duty cycled collection. As the duty cycle is shortened, both reliability and energy consumption decrease. For 5% duty cycle-based collection, reliability is more than halved and energy consumption is approximately 12% that of the 100% duty cycle. (This is in agreement with previous studies [13].) Ranging experiments concern measuring reliability and latency of WuR-based data collection at varying horizontal and vertical distances.[2] We find that, at vertical distance 5 m, reliability is 93% at horizontal distance 5 m, and monotonically reduces to 49% at 25 m. Latency is mostly consistent at this altitude, with data exchange successfully completing in an average of approximately 27 ms. At vertical distance 10 m, reliability drops significantly, with a maximum of 20% and a minimum of 2%. Latency remains consistent until a horizontal distance of 20 m, at which point it begins increasing.

To the best of our knowledge, there are no prior experimental investigations using drones in the field. Previous works exploring the benefits of using drones for data collection in WSNs evaluate the performance of their solutions by simulations [14], [11], [15].

The remainder of the paper is organized as follows. Section II describes the protocols used and the scenarios considered for our experiments. Section III describes the experimental setting and depicts the experimental evaluation of the performance of mobile data collection. Finally, Section IV concludes the paper.

II. EXPERIMENT DESIGN

This section describes the protocols, settings and the design of our experiments. We examine different aspects of mobile data collection by designing multiple data exchange protocols (Section II-A). We investigate our testing system constraints to determine the boundaries of performance for core facets of mobile data collection (Section II-B). We finally define our ranging experiments to measure the performance of data exchange at varying distances (Section II-C).

A. Protocols

Four data exchange protocols are used in our experiments. Each of these protocols requires at least two motes. One mote is mounted on the UAV, forming the MDC. The other is placed on the ground, acting as an SN. The protocols are as follows:

1) Round-Trip. Both the MDC and the SN keep their main radios and WuRs on throughout. For each run, the MDC broadcasts a WuS. When the SN receives the WuS, it responds with an ACK. For this protocol we measure:
   Success: The MDC receives the ACK.
   Latency: The time between the MDC broadcasting the WuS and receiving the ACK.
2) Awakening & Round-Trip. The MDC keeps both its main radio and WuR on throughout. The SN keeps its WuR on and main radio initially off. For each run, the MDC broadcasts a WuS. When the SN receives the WuS, it turns on its main radio and responds with an ACK. After sending the ACK, the SN turns off its main radio.
   Success: The MDC receives the ACK.
   Latency: The time between the MDC broadcasting the WuS and receiving the ACK.
3) Packet Collection using WuR. The MDC keeps both its main radio and WuR on throughout. The SN keeps its WuR on and main radio initially off. For each run, the MDC broadcasts a WuS. When the SN receives the WuS, it turns on its main radio and responds with a data packet. When the MDC receives the data packet, it sends back an ACK. When the SN receives the ACK, it turns off its main radio.
   Success: The SN receives the ACK.
   Latency: The time between the MDC broadcasting the WuS and the SN receiving the ACK.
4) Packet Collection using Duty Cycling. The MDC keeps its main radio on throughout. The SN turns its main radio on and off at periodic intervals, maintaining a fixed duty cycle. The duty cycling technique used by the SN is *preamble sampling* with *short preambles*. The WuRs are not used. For each run, the MDC broadcasts a *Request To Send* (RTS) control packet. When the SN receives the RTS, it responds with a data packet. When the MDC receives the data packet, it sends back an ACK.
   Success: The SN receives the ACK.
   Latency: The time between the MDC broadcasting the RTS and the SN receiving the ACK.

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[1] Reliability is defined as the number of times a data exchange protocol successfully completes divided by the total number of times that protocol is run (Section III-A).

[2] Latency is defined as the total amount of time taken for a data exchange protocol to successfully complete (Section III-A).

B. Calibrations

In the calibrations, the aim is to test the following:

1) For how long can the UAV carry a mote?
2) At what distances can the MDC consistently communicate with an SN on the main radio? (No use of WuRs.)
3) At what distances can the MDC consistently awaken and communicate with an SN? (Use of WuRs.)
4) How does the performance of data collection differ when using WuR and when using duty cycling?

For test 1, no data exchange occurs between the mote radios. This test is used to determine the flight characteristics of the MDC, including an upper bound for a data collection cycle.

Tests 2 and 3 use protocol 1. (For test 2, protocol 1 is modified to use an empty data packet instead of a WuS.) In both tests, the MDC and SN are initially at different locations. The MDC takes off and flies overhead, moving towards the location of the SN, intermittently running its data exchange protocol. After moving sufficiently close, the MDC hovers above the SN for a short period. Finally, the MDC returns to its starting point. The initial horizontal distance between the MDC and the SN is varied. The reliability of data exchange is monitored throughout the data collection cycle.

For test 4, protocols 3 and 4 are evaluated over an extended duration. This is done because the maximum length of a data collection cycle (as determined in test 1) is not sufficient for obtaining meaningful measurements of the energy consumption of these protocols. The duty cycle of protocol 4 is varied. The reliability and energy consumption of both data collection protocols are measured and compared.

C. Ranging

In the ranging experiments, an additional 'sniffer' mote is used as the experiment controller. The sniffer is a specialized variant of the base mote. It sports a particularly sensitive main radio and no WuR. It is connected to a computer in the vicinity, and is used to launch experiments and collect metrics.

Three scenarios are considered:

1) Indoors, with the MDC mounted on tripods (not in flight).
2) Outdoors, with the MDC mounted on tripods (not in flight).
3) Outdoors, with the MDC in flight.

Scenarios 1 and 2 are contrived to provide a baseline for the experiments with scenario 3. For each scenario, protocols 1, 2 and 3 are run with varied distances between the MDC and SN. In scenarios 1 and 2, the parameter varied is the horizontal distance. In scenario 3, both the horizontal and vertical distances are varied.

III. EXPERIMENTAL EVALUATION

A. Metrics

We investigate the following metrics.

- Reliability: The percentage of successful runs of a given protocol.
- Latency: The total amount of time taken to complete a successful run of a given protocol.
- Energy Consumption: The energy consumed over the course of an experiment.

B. Setup and Execution

In all our experiments, we use WuR-enabled ultra-low-power *MagoNode++* motes [16]. This model has been extensively characterized [13], [17] and used in a wide variety of applications [10], [12], [18]. It has proven to be both versatile and robust, making it an ideal model for our experiments. For the UAV, we use a DJI Matrice 100 outfitted with a Pixhawk flight controller [19] operating with Arducopter. This model is relatively small and maneuverable with an approximate flight time of 16 minutes with a 1 kg payload. The on-board computer is a Raspberry Pi 3B. The ground station computer connected into the Pi via a Wi-Fi connection in order to start the flight control program on the Pi.

In the implementation of the experiment programs, motes are instructed to resend WuSs or packets if an expected response is not received before a timeout occurs. For instance, in protocol 3, when the MDC sends a WuS, it expects a data packet from the SN. Similarly, when the SN sends the data packet, it expects an acknowledgement from the MDC. If the expected response is not received within a specified timeout, the sender tries again. This is repeated until a maximum number of retries is reached, after which the WuS or packet is considered lost. However, if any of the retries are successfully responded to, the latency of the run is increased by a multiple of the delay between retries.

- **Calibrations**. Calibrations 1 to 3 were conducted at Franklin Park, Boston, MA, U.S.A. Specifically, the baseball field at Franklin Park Playstead, south of White Stadium. For our convenience, the MDC was placed at a fixed starting location, while the SN was placed at different locations around the field. The initial distance between the MDC and SN were varied in the range $\{25, 50, 75, 100, 150, 200\}$ m.

Calibration 4 was conducted indoors. Protocols 3 and 4 were run 2500 times per experiment. The duty cycle of protocol 4 was varied in the range $\{100, 50, 10, 5\}\%$.

- **Ranging**. Scenario 1 of the ranging experiments used the lobby of the Interdisciplinary Science and Engineering Complex (ISEC), which is located on the campus of Northeastern University. The horizontal distance between the MDC and SN was varied in the range $\{2, 4, 6, 8, 10\}$ m.

Scenario 2 of the ranging experiments used the Carter Playground football field, located just north-east of ISEC. The horizontal distance between the MDC and SN was varied in the range $\{2, 4, 6, 8, 10, 15, 20, 25\}$ m.

Scenario 3 of the ranging experiments once again used Franklin Park Playstead. Fig. 1 depicts the setup. Expressing the horizontal and vertical distances (m) as a pair (h, v), the distances were varied in:

$$\left\{ \begin{matrix} & (10,10)\,, & (15,10)\,, & (20,10)\,, & \\ (5,5)\,, & (10,5)\,, & (15,5)\,, & (20,5)\,, & (25,5) \end{matrix} \right\}$$

For all scenarios, each protocol was run 100 times per experiment.

Fig. 1. Outdoors scenario, MDC in flight, SN on a tripod.

C. Results

• **Calibrations**. The results of the calibrations provide useful information for the design of mobile data collection protocols and experiments. In general, it is found that:

1) The UAV is able to carry a mounted MagoNode++ mote for up to approximately 16 minutes, depending on wind and other weather conditions.
2) The main radios on the MagoNode++ motes are able to communicate at greater-than-expected distances while the MDC is in flight (up to approximately 200 m).
3) The WuRs on the MagoNode++ motes are able to communicate at expected distances while the MDC is in flight (in agreement with Basagni et al. [17]).
4) Fig. 2 illustrates the performance of data collection using WuR and that of using duty cycling. The reliability of protocol 3 is nearly identical to that of protocol 4 with a duty cycle of 100% (i.e., the main radio is always on). As the duty cycle shortens, both the reliability and energy consumption decrease, as expected. However, the energy consumption of protocol 4 is never lower than that of protocol 3. In fact, even at the lowest duty cycle, the energy consumption of protocol 4 is over 4 times that of protocol 3. At the highest duty cycle, this increases to over 36 times that of protocol 3. Therefore, packet collection using WuR technology is consistently more energy efficient than that with duty cycling, without sacrificing any reliability (in agreement with Basagni et al. [13].).

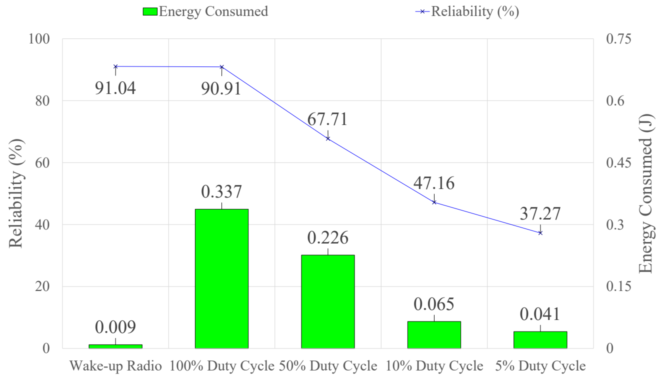

Fig. 2. Reliability of data collection with WuR and duty cycling.

• **Ranging**. The results of the ranging experiments provide meaningful information about the reliability and latency of the protocols. However, the energy consumption was consistently imperceptible. Thus, the results from protocol 4 are not particularly relevant here, as its purpose is to contrast the energy consumption with that of protocol 3.

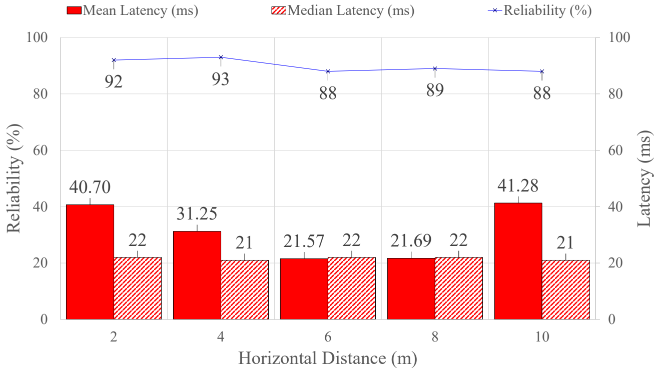

Fig. 3. Indoors, round-trip.

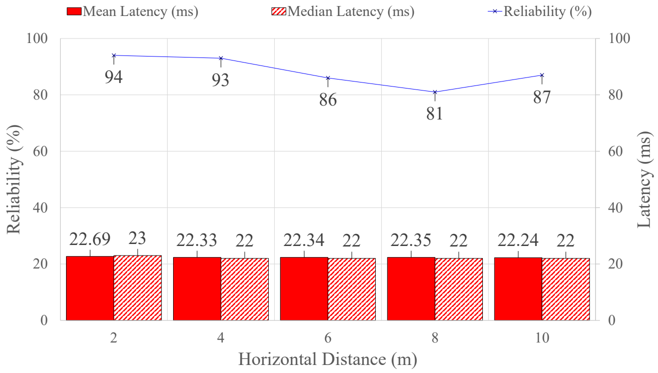

Fig. 4. Indoors, awakening & round-trip.

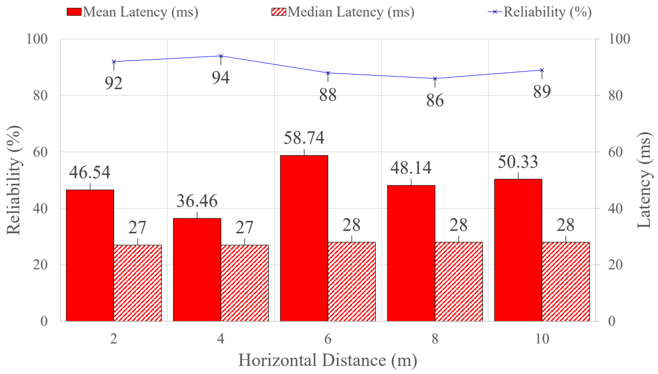

Fig. 5. Indoors, packet collection using WuR.

Figures 3, 4, and 5 illustrate the results for scenario 1. The reliability is consistently high across the board, with the mean reliability at approximately 89%. Due to the indoors environment and relatively short ranges, most WuSs are successfully delivered and responded to. The latency is also generally consistent, with a mean of approximately 34 ms and a median of 22 ms. Some extreme outliers cause the mean latency to get inflated. These outliers are likely the result of dropped WuSs or packets, leading to retries. Such outliers are detected in subsequent ranging experiments as well.

The performance of the protocols do not differ significantly in most respects. However, the median latency for protocol 3 is consistently greater than the equivalent median latency of protocols 1 and 2. This is due to the additional leg of the data exchange circuit in protocol 3. Additionally, the median latencies do not significantly differ between protocols 1 and 2. The time required by the SN to awaken its main radio is relatively insignificant compared to the round-trip time.

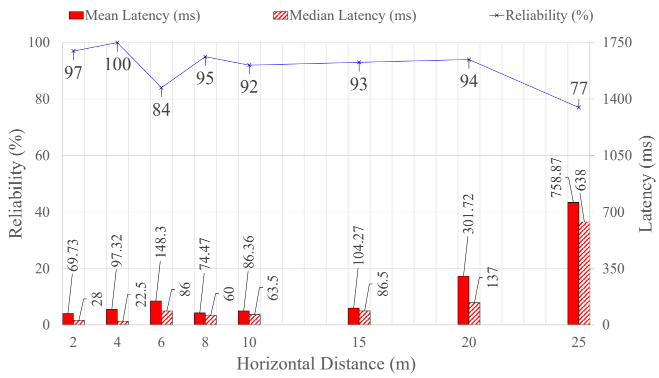

Fig. 6. Outdoors (not in flight), round-trip.

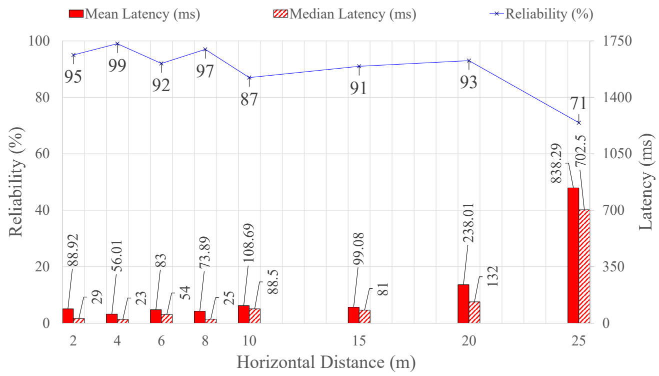

Fig. 7. Outdoors (not in flight), awakening & round-trip.

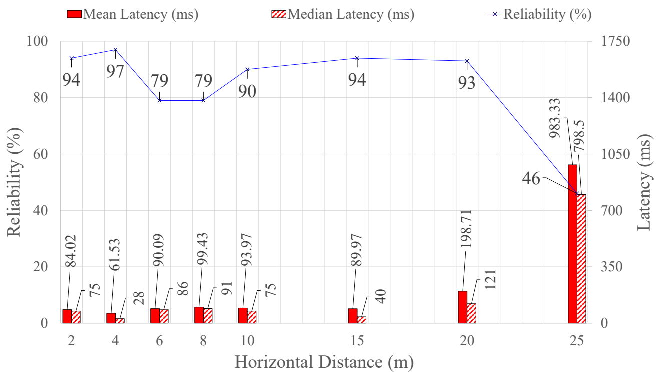

Fig. 8. Outdoors (not in flight), packet collection using WuR.

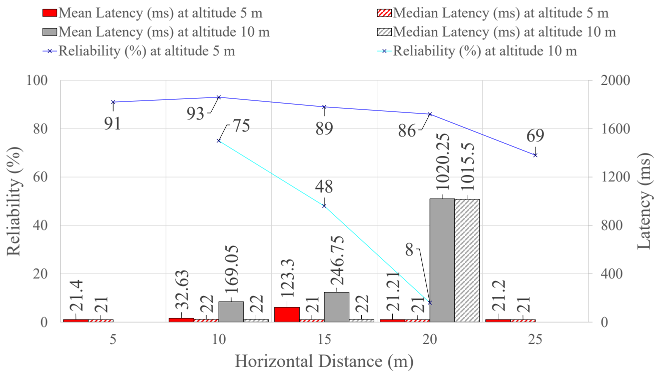

Fig. 9. Outdoors (in flight), round-trip.

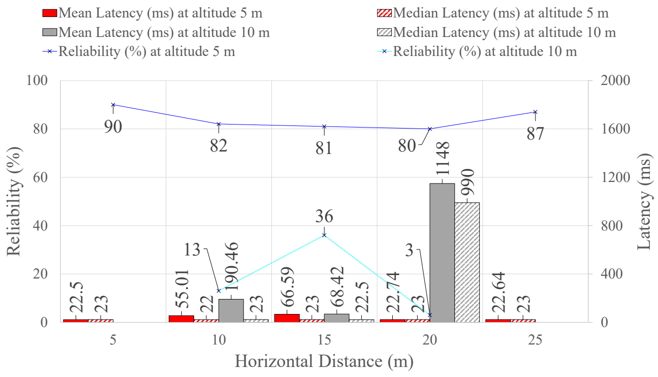

Fig. 10. Outdoors (in flight), awakening & round-trip.

Figures 6, 7, and 8 illustrate the results for scenario 2. The reliability is generally high ($\geq 79\%$) up till a horizontal distance of 20 m, but drops significantly at 25 m. Latency also increases with horizontal distance, again due to retries for dropped WuSs or packets. As the likelihood of packets dropping increases with distance, so too does the effective latency of a successful run.

Figures 9, 10, and 11 illustrate the results for scenario 3. As expected, the reliability tends to decrease with horizontal distance. Interestingly, the vertical distance has a much greater effect on reliability. Beyond an altitude of 5 m, the reliability drops significantly. We observe that reliability is affected differently by vertical and horizontal distances. This is due to the radiation pattern of the WuR antennae.

The latency at altitude 5 m is lower than expected. In scenario 3, latency increased with horizontal distance. However, when the MDC is at an altitude of 5 m, the latency is generally consistent, barring the occasional outlier. This indicates that performance of data exchange improves with altitude, up until approximately 5 m, beyond which it worsens. At an altitude of 10 m, the latency behaves as expected, increasing with horizontal distance.

IV. CONCLUSIONS

Mobile data collection with an aerial MDC facilitates the collection of data packets from WSNs where routing is impossible, or even just unfeasible. While the MDC can be recharged when it returns to a base station at the end of each collection cycle, the power consumption of the WSN nodes is still a limiting factor in network lifetime. Duty cycling and WuR technology can ameliorate this by significantly reducing the amount of time a node's main radio spends idling. In this study, we examine the performance of both techniques applied to mobile data collection. In particular, we perform an experimental evaluation of WuR-based collection, its implementation, and its limitations. We conduct multiple sets of experiments with protocols that exemplify different facets of data collection. We consider an indoors scenario, an outdoors scenario with the MDC not in flight, and an outdoors scenario with the MDC in flight. Our results show that when the MDC is in flight, data collection is best at an altitude of 5 m, with reliability ranging between 93% and 49% (decreasing monotonically with horizontal distance) and latency consistently around 27 ms. We also contrast the longitudinal performance of collection using WuR vs. collection using duty cycling. We find that a 100% duty cycle-based collection consumes over 36 times the energy of WuR-based collection, with similar reliability rates, whereas a 5% duty cycle consumes over 4 times the energy of WuR with less than half the reliability.

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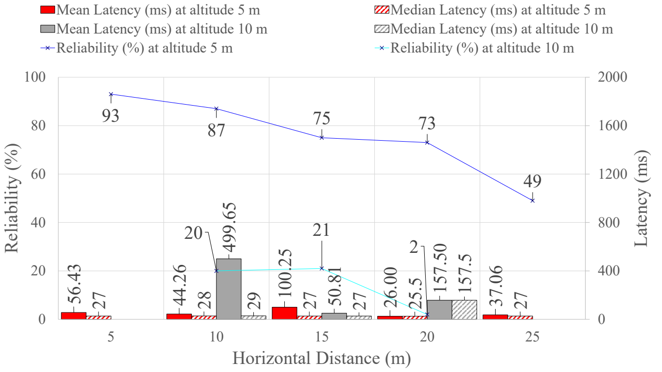

Fig. 11. Outdoors (in flight), packet collection using WuR.

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