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Athlete Tracking at a Marathon Event with LoRa: A Performance Evaluation with Mobile Gateways †

Dominik Hochreiter

Institute for Pervasive Computing, Johannes Kepler University, 4040 Linz, Austria ; hochreiter@pervasive.jku.at

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Abstract: Accurate and continuous location monitoring of athletes helps meeting health and safety requirements and supporting the infotainment needs of large marathon events with thousands of participants. Currently the tracking of individuals and groups of athletes at mass sports events is only possible to a limited extent, due to weight, size and cost constraints of the necessary devices. At marathon events, the usual infrastructure for timekeeping is Radio Frequency Identification (RFID) technology, which allows only precise tracking at huge intervals, with heuristic and interpolative algorithms to estimate runner positions in between the measuring points. Setting up RFID tracking stations on site is also material and labour intensive. We instead propose a continuous, real-time tracking solution, relying on Long Range Wide Area Network (LoRaWAN) GPS trackers. Due to the large geographical area and urban space in which marathon events take place, the positioning of static gateways cannot provide complete and continuous coverage. This research article presents an implementation with multiple LoRa trackers and mobile LoRa gateways installed on vehicle escorts to assess coverage quality. The tracking data collected by a receiving LoRaWAN Network Server (LNS) is stored in a database. Three experiments were conducted at three different official running events, a 10 km race, a half marathon and a marathon. The backdrop for 42.195 km was the official Vienna City Marathon 2024 with more than 35,000 participants. The experimental results under these realistic conditions show the reception quality of this approach, e.g., during the marathon, received packets from LoRa gateways were at an average distance of about 136 m (σ 157m) from the tracker with a median update rate of 31 s across all trackers, using DR3/SF9. At greater distances, the quality decreases, although some outliers were received up to a distance of two kilometres. A possible prospect is that Low Power Wide Area Network (LPWAN) may repeat the history of RFID by entering the mass sports market from the industry domain.

Keywords: Athlete Tracking; Wireless Sensor Nerworks (WSNs); Low-Power Wide-Area Network (LPWAN); Long Range (LoRa); Runners; Monitoring

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1. Introduction

Looking for a new technological approach for continuous athlete tracking, this study evaluates the feasibility of LoRaWAN to meet this requirement. Current solutions, such as RFID-based timing systems, allow only estimates of a runner's potential positions during the race. Other technologies are limited to some extent by the weight, size, and cost of the equipment required. The work is driven by the fundamental question of whether this technological approach is potentially lightweight enough for use by elite runners, who expect the tracking device to weigh no more than a few grams, comparable to a passive RFID tracking chip. Is it durable enough for a full race event with additional spares, what are typical power consumption profiles? Is the range sufficient in terms of radio transmission distance, what kind of antenna geometry must be used?

Continuous athlete tracking during a marathon is essential to ensure the safety, performance, and overall experience of participants, as well as to meet infotainment needs. Marathon runners often push themselves to their physical limits, leading to potential health issues such as dehydration, heat exhaustion or cardiac events. By monitoring athletes' locations in real-time, race organizers can quickly identify and assist those in distress, potentially preventing serious injuries or fatalities. In addition, continuous tracking improves the accuracy of race logistics, ensuring fair competition and efficient resource management. It provides valuable data for performance analysis, helping athletes and coaches improve training and strategy. From an infotainment perspective, continuous tracking allows spectators and fans to become more involved in the event by providing real-time updates and interactive experiences as they follow their favorite runners, boosting morale and increasing viewer engagement.

For the experimental evaluation, a set of LoRa getways and trackers were assembled and equipped with mounting material. Appropriate software and network configurations were deployed for a mobile outdoor test setup. Several experiments were conducted during different running events in an urban environment. Different device configurations in terms of GPS update rates or data rate settings were used during data acquisition, as well as the impact of mobile versus static LoRa getaways.

The remainder of this paper is organized as follows. Section 2 presents some related work. The proposed solution and the hardware used are explained in Section 3. Section 4 describes the experiments and the results obtained. Finally, Section 5 presents the discussion, the main conclusions, and future work.

2. Related Work

This section presents some related works. For the context of a running event in an urban environment, the range and coverage of LoRaWAN is a decisive criterion. The standard Long-range (LoRa) in the 868 MHz band covers a range of 5–10 km; the actual capacity and range of LoRa 2.4 GHz drops to 700 m when the target Packet Delivery Ratio (PDR) increases to 90%, accommodating 120 nodes, according to Falanji et al. [1]. The coverage measurements in an urban scenario for Point-to-Point LoRa connections from Callebaut et al. [2] indicate a distance of up to 1km. The interference measurement study in the 863–870 MHz band from Lauridsen et al. [3] in a European city shows that there is a 22–33% probability of interfering signals above −105 dBm within the mandatory LoRa MHz band in a shopping area and a business park in downtown. General limitations of LoRaWAN, for example, are that deterministic monitoring and real-time operation cannot be guaranteed; the combination of the number of end devices and gateways, the selected SFs, and the number of channels will determine whether LoRaWAN ALOHA-based access and maximum duty cycle regulation are suitable for the use case [4].

In long-distance races such as cross-country or marathon championships, the continuous tracking of pace profiles and tactical behaviors of runners requires a high observation resolution. It allows the runner to analyze their decisions so that these athletes can develop more optimal and successful behaviors [5]. Solutions such as drone systems equipped with depth cameras are experimental and not practical for mass events and recreational runners [6].

Pandey et al. [7] reported on the needs of recreational athletes who were unable to track sport-specific techniques due to the limitations of tracking technologies and wished for better tracking support for these. Venek et al. [8] report in their review that sensor technology has been used in studies to assess quality of movement, but translation from the lab to the field in recreational and professional sports is still emerging.

A study by Sendra et al. [9] proposes a low-cost system that utilizes low-power wide-area network (LPWAN) technology to monitor the positions and vital signs of runners in cross-country races. Existing tracking systems only confirm the passage of checkpoints and do not provide continuous status monitoring. Each runner carries a device that transmits data and has an SOS button for emergencies. The paper contains the design and experiments to support this system. For the experiments, they used a single, stationary LoRa Gateway. They did not test the scalability or the special circumstances of a mass event in a city.

The common approach, as described by Dabhade et al. [10], to track athletes in marathons is passive RFID trackers. They have no internal power source and are powered by the electromagnetic energy transmitted by an RFID reader. They are small and can be integrated into race bibs, for example. Typically, RFID readers are placed at the start and finish lines, with a few scattered along the course to measure time. This means a lack of resolution for continuous tracking.

3. Materials and Methods

The proposed architecture for tracking runners in an urban environment at running events consists of selected LoRa tracker devices, receiving gateways that act as proxies for a LoRaWAN Network Server (LNS), which in turn makes the data available to third-party applications, as shown in Figure 1. The trackers are worn by the runners, usually on the upper arm or fixed to the waist, and the gateways are carried by cars or by bicyclists. The collected position information was stored in a database and live visualized on a web interface.

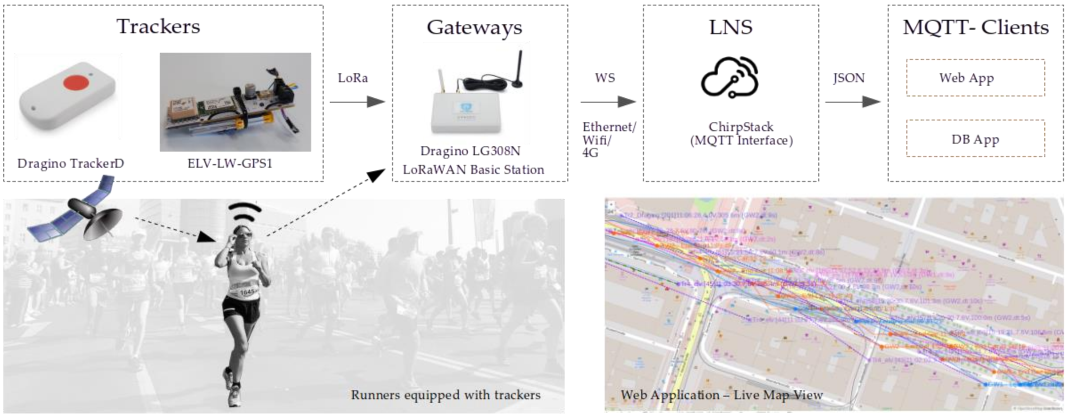


Figure 1. Architecture and selected hardware components for our mobile LoRa-based system for tracking runners in city races and marathons. Above is the data acquisition and communication chain. Bottom left, idealized: a selected runner is tracked. Bottom right, the collected positions, each point containing a description of when it was received, from which GW, the distance to it, and how far the time step was from the last known GPS position of the GW.

3.1. Hardware

Two different types of LoRa Tracker devices were used to track the runners. The open-source Dragino TrackerD, which uses a SX1276/78 module and operates in LoRaWAN Class A mode at an 862 Mhz frequency range, is equipped with GPS, a microcontroller and a 1000 mA Li-on battery. The device is Arduino IDE compatible and we used platformIO to upgrade it to the latest firmware version (1.4.6), which allows us to keep the GPS module (Quectel L76) always on and powered, which improves the fix accuracy and shortens the acquisition time for the next uplink. It increases the power consumption up to 50 mA. The second type of tracker we used was the ELV-LW-GPS1 from ELV, a simple development platform equipped with GPS (Quectel LC86L) and operating in LoRaWAN Class A mode at 862 Mhz. We wired LiPo batteries (2× 400 mAh/3.7 V) to the platform so that it could run standalone. We also added a simple on/off and charge switch.

In total, we conducted the experiments with four trackers, two Dragino TrackerDs (Tr1,Tr2), and two ELV-LW-GPS1s (Tr3,Tr4). The usual operating modes in all experiments were that the adaptive data rate (ADR) was disabled, the devices were configured to send continuous updates at configurable intervals, and we used different settings in the experiments. For TrackerD, we used the configuration option to set the GPS acquisition find timeout in seconds. Different values were used in the experiments. A long GPS acquisition time affects the overall update rate by slowing it down. Configuration of the devices was done wired using the USB interface or remotely using the upload queue from the ChirpStack [11] LNS server interface. For both trackers, we installed a custom message decoder on the LNS to make the positioning data accessible.

Under the constraints of upload payload size, for example, DraginoD uplink payload includes a total of 11 bytes without protocol overhead size, and airtime regulations, and most bands use a maximum duty cycle of 1%, we planed the minimum supported update rate for our tracking positioning should be 30 s. If we consider an average runner with a marathon time of 4 h and a running pace of 10.5 km/h, this means an update every 87.5 m of distance. In the case of an elite runner and a pace of 20 km/h, the update could occur every 166.7 m. This suggests a minimum data rate (DR) setting of 3, a spread factor (SF) of 9, and a bandwidth (BW) of 125 kHz, which allows update rates of less than 30 s. The tracking resolution varies with the speed of the runner. Fast update rates would be desirable, but the shorter airtime affects the coverage that our pre-tests showed.

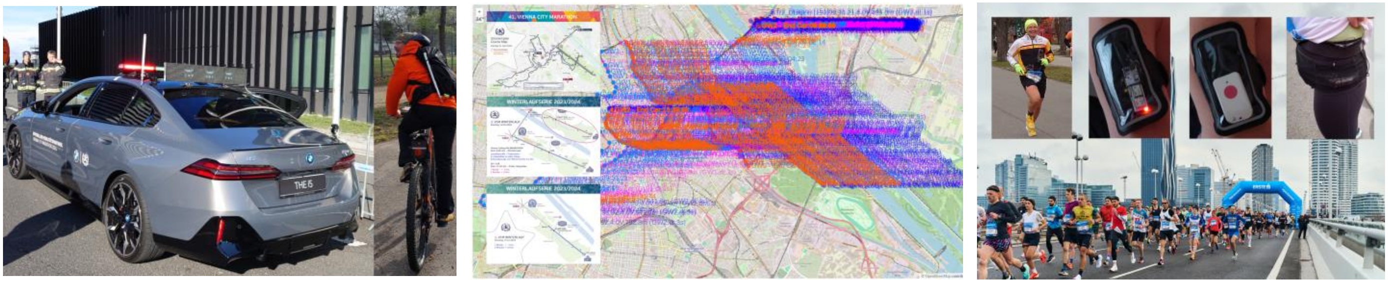
For the gateway, we used an LG308N from Dragino, which allows you to bridge a LoRa wireless network to an IP network via WiFi, Ethernet, 3G or 4G cellular network. The software stack is open source and uses an ar9331 processor. It uses a Semtech packet forwarder and is fully compliant with the LoRaWAN protocol. It includes an SX1302 LoRa concentrator that provides 10 programmable parallel demodulation paths. The Tx power is up to 27 dBm and the RX sensitivity is up to −142.5 dBm. It supports multiple frequency bands, we used the EU868. We operated two mobile gateways, one of them, gateway one (GW1), we replaced the standard antenna with a 40 cm long fiberglass antenna (Dragino BLG-AN-040-R), while gateway two (GW2) uses the standard antenna. In some urban pretests, GW1 showed an improvement in range of up to 100 m. For the outdoor tests, we used a 4G uplink to connect to the LNS. The gateways were powered by lead-acid batteries. To collect the GPS location of the GWs, we attach a smartphone with a tracking app that sends the location in real time to our web application.

3.2. Software and Communication

To connect the GWs to the LNS, we used the LoRa Basics™ Station, an implementation of the LoRa Packet Forwarder. [12]. We used web socket (ws) connections to connect to the LNS. We ran a ChirpStack LNS server that distributed our tracking data to a web application and a process that stored the data in a MariaDB database [13]. The connection is established using MQTT and JSON messages. A broker is provided by the LNS implementation. The data contained in the JSON message includes the LoRa overhead data (e.g., DR, SNR or reception time) and the payload data of the trackers, e.g., GPS or battery voltage data. The implementations are written in Perl and various bash and web scripts. The frontend web visualization uses OpenLayers [14], shown in Figure 1c.

4. Results

This section describes how the measurements were taken and the results obtained in terms of performance measures and data distribution. We deployed this approach at three urban running events in Vienna, in the following chronological order: the first being a 10 km run with about a thousand starters, the second a half marathon with one and a half thousand starters, and the third a full marathon with more than 30,000 starters. At each event, we equipped four runners with our trackers and deployed two gateways on-side. The gateways were always mobile, attached to a bike or car (Figure 2a), which followed the runners. The exception was the first event, where we had only one mobile gateway, the other one was positioned along the track. The running tracks are shown in the foreground of Figure 2b, the background shows the entire data collection of the full marathon race along the track.



(**a**) (**b**) (**c**)

Figure 2. Overview of our settings at three running events (**a**) Shows the mounting position of the fiberglass antenna of GW1 on the mobile escort, GW2 uses the standard antenna on the second; (**b**) Shows in the background the geographical area of the Vienna City Marathon and the collected GPS positions of the LoRa trackers at the full marathon event; in the foreground, the tracks of the three events are shown, from top: Marathon, Half marathon, 10 km Run (**c**) Usual wearing positions of the trackers: Upper arm or side of the waist.

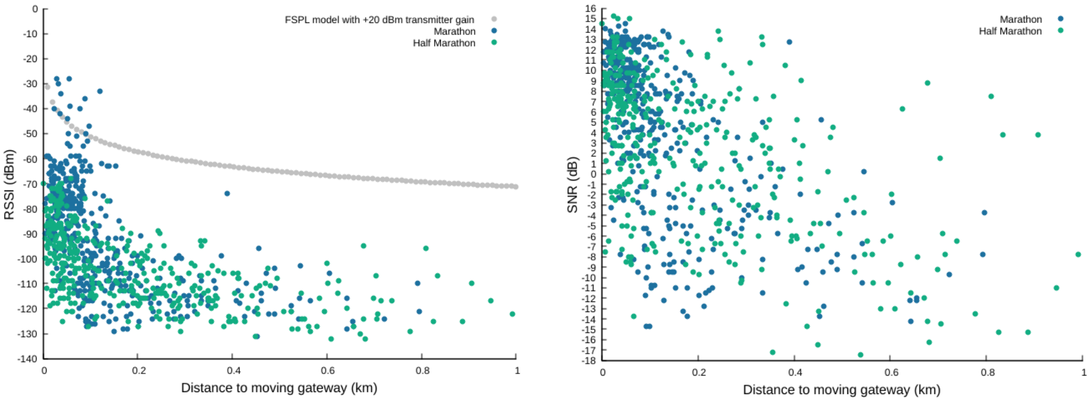
The volunteer runners were hobby and recreational athletes of varying ability levels. Each athlete had the choice of wearing the tracker on their waist or upper arm, as shown in Figure 3c. For the full marathon event, we decided to use two cyclists to simulate elite runners and attached the trackers to them, running at the front of the field to mimic elite runners.

The data collection setup for all three events is shown in Table 1. The table summarizes the runner type and tracker setting for each event. It shows the amount of data collected. It gives an indication of the average update interval, run time, and coverage. The gap time shows the longest observable period without receiving data from a given tracker. Finally, it shows the averaged radio performance metrics.

Table 1. Summary of the captured data of the three running events.

Trackers	**Tr1 (Dragino)**	**Tr2 (Dragino)**	**Tr3 (ELV)**	**Tr4 (ELV)**	**Aggregation**
Experiment—Full Marathon					
Runner Type/DR(SF)	Elite/DR3(SF9)	Hobby/DR3(SF9)	Elite/DR3(SF9)	Hobby/DR3(SF9)	
Pkgs Recv. GW(1/2) [1]	89 (84/5)	297 (109/188)	198 (186/12)	82 (31/51)	666
Updates ⌀/~x	34/31 s	98/34 s	68/30 s	351/29 s	138/31 s
Run/Gap-time	50/1.6 min	484/51 min	224/40 min	474/159 min	308/63 min
Distance ⌀/σ/max	62/25/109 m	137/188/1480 m	150/123/565 m	122/79/365 m	136/157/630 m
RSSI(dBm)/SNR(dB) ⌀	−69/7.4	−83/6.4	−101/2.4	−110/−3.2	−91/3.2
Experiment—Half Marathon					
Runner Type/DR(SF)	Hobby/DR4(SF8)	Hobby/DR2(SF10)	Hobby/DR3(SF9)	Hobby/DR1(SF11)	
Pkgs Recv. GW(1/2) [2]	89 (66/23)	59 (36/23)	138 (93/45)	125 (91/34)	411
Updates ⌀/~x	90/23 s	123/60 s	57/30 s	63/31 s	83/36 s
Run/Gap-time	132/81 min	119/55 min	132/15 min	131/16 min	129/42 min
Distance ⌀/σ/max	313/352/1916 m	193/213/991 m	216/286/1366 m	290/162/1730 m	256/322/1501 m
RSSI(dBm)/SNR(dB) ⌀	−104/5.1	−100/3.5	−105/1.1	−104/0.4	−103/2.5
Experiment—10 km Run					
Runner Type/DR(SF)	Hobby/DR3(SF9)	Hobby/DR2(SF10)	Hobby/DR1(SF11)	Hobby/DR4(SF8)	
Pkgs Recv. GW(1/2) [3]	27 (13/14)	35 (26/9)	100 (24/76)	75 (49/26)	237
Updates ⌀/~x	35/25 s	77/58 s	30/29 s	44/31 s	47/35 s
Run/Gap-time	15/3 min	43/4 min	50/1 min	55/3 min	41/3 min
Distance ⌀/σ/max	487/262/1014 m	522/302/1147 m	318/234/740 m	545/325/1165 m	483/308/1017 m
RSSI(dBm)/SNR(dB) ⌀	N/A [4]	N/A	N/A	N/A	N/A

[1] Gateways: GW1 was in the "Lead" car (shown in Figure 2a), GW2 was in the "End" car. [2] Gateways: GW1 was in the "Runners field" bike, GW2 was in the "Leading female" bike. [3] Gateways: GW1 was stationary, GW2 was in the "Runners field" bike. [4] N/A: Data was not collected.

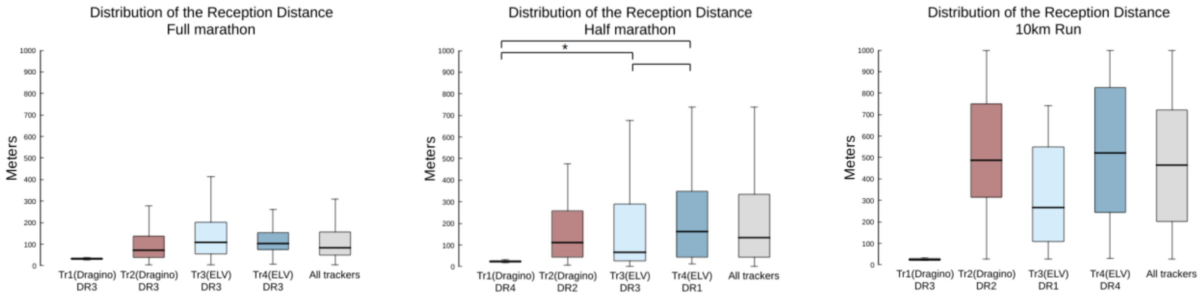


(**a**) (**b**)

Figure 3. Shows the value of RSSI and SNR as a function of distance from the gateway. (**a**) Compares the recorded RSSI of our collected half and full marathon data with the FSPL model estimates; (**b**) Shows the SNR for the same data.

Regarding the performance of the wireless network, we analyzed the Received Signal Strength Indicator (RSSI) and the Signal to Noise Ratio (SNR) of our collected data, which indicate the quality of our signal and service. In Figure 3, we show the value of RSSI and SNR as a function of the distance from the gateway. The 10 km event is not part of the comparisons as we did not collect this information. The LoRa RSSI results are compared to the Free Space Path Loss (FSPL) model for RSSI prediction [15], shown in Figure 3a. Our results show a behavior away from the ideal model, as expected, and even worse compared to the results of the study in a more rural area [9]. Figure 3b shows the value of SNR, we can see that there is a large variation. As a result of the distance and the presence of objects, the transmitted signal is reflected and refracted.

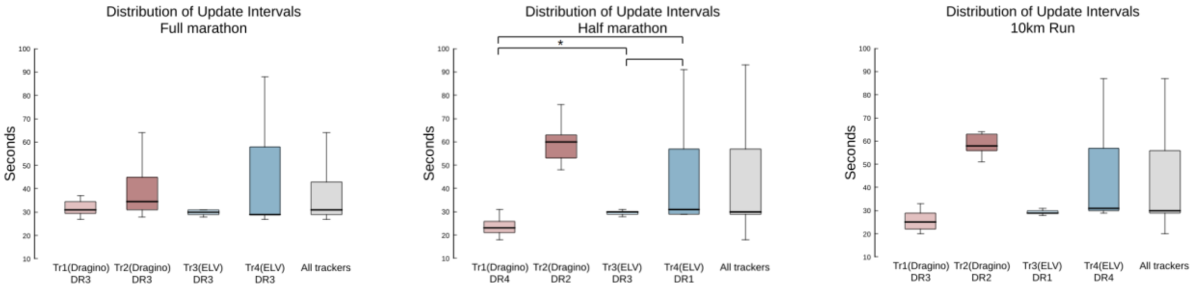
To answer our initial questions about update rates and range, we evaluated the distribution of our collected data. In Figure 4, the box plots show the reception distance to the GWs for each event. The whiskers of the box plots indicate values within 1.5 times the interquartile range, and outliers are suppressed. For the 10 km run (Figures 4c and 5c), one of the GWs was stationary along the track. The second was worn by a cyclist in the middle of the runners. In the half-marathon event, two cyclists were equipped with GWs, one was the support cyclist for the elite female field (GW1) following that group, and the other was in the mass of runners. In the full marathon event, GW1 was installed on the lead support vehicle and the second was installed on the finish vehicle. For the full marathon event, we measured an average reception distance of 136 m (σ 157m).



(**a**) (**b**) (**c**)

Figure 4. The reception distance of our trackers during running events. (**a**) The full marathon. (**b**) Half marathon, here we compared the significance between the different tracker settings. (**c**) The 10 km run.

To evaluate the update rates, we did the same as shown in Figure 5. The plots show the distribution of the observed update rates for all four trackers at the different running events.



(**a**) (**b**) (**c**)

Figure 5. The position update rate of our trackers during running events. (**a**) The full marathon. (**b**) Half marathon, here we compared the significance between the different tracker settings (* $p < 0.05$). (**c**) The 10 km run.

We analyzed the effect on coverage for different DR settings. To see if there was a significant difference between lowest and highest DR settings, we used a two-tailed independent t-test with an alpha significance level of 0.05 for our half marathon data collection (Figures 4b and 5b). We used the statistical analysis tool GNU PSPP for the paired t-test. We compared the trackers using DR1 vs. DR4, DR4 vs. DR3, and DR1 vs. DR3, as well as for the reception distance and update interval measures. The null hypothesis ($p < 0.05$) is not rejected in all cases, except for the reception distance, using DR4 and DR3 ($p = 0.033$). We decided to use only the DR3 setting for the full marathon event for all trackers. This matches the observations in our preliminary studies and is consistent with our target position update rate of every half minute. The observed median of the update rate was 31 s for the full marathon event.

5. Discussion and Conclusions

In this paper, we have presented the design of a LoRa-based tracking system for runners and evaluated its performance in urban running events. It is important to note that the data we collected from the different events is not exactly comparable. The positioning of the runner in the field and the accompanying vehicle, whether bicycle or car, are different between them. The chosen DR3 value seems to be a good compromise between a possible tracking update rate limited by LoRa's airtime regulation and the reception of the trackers' position. The airtime regulation argument was also a reason why we did not consider using the community-based The Things Network (TTN) [16]. The power consumption of the trackers is not an issue, e.g., the lipo battery of the marathon event was depleted by 0.1 V, measured at the end of the event. The position of the wearer and the size of the antenna have some impact on the reception quality, which some pre-tests have shown, e.g., the human body shields the signal, this needs to be further analyzed in a future study.

Another LPWAN-based approach for future work could be Mioty, a completely software-based wireless technology that is hardware-independent and uses Telegram Splitting Multiple Access (TSMA) for transmission. A comparative study [17] showed that the reception distance for an urban area could potentially be increased.

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