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Real-time Data Dissemination and Analytics Platform for Challenging IoT Environments

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***Abstract*—The advent of Internet-of-Things (IoT) applications, such as environmental monitoring, smart cities, and home automation, has taken the IoT concept from hype to reality at a massive scale. However, more mission-critical application areas such as energy, security and health care do not only demand low-power connectivity, but also highly reliable and guaranteed performance. While fulfilling these requirements under controlled conditions such as urban and indoor environments is relatively trivial, tackling the same obstacles in a more challenging and dynamic setting is significantly more complicated. In environments where infrastructure is sparse, such as rural or remote areas, specialized infrastructure-less ad-hoc solutions are needed, which provide long-range multi-hop connectivity to remote sensors and actuators. In this paper we propose a new general-purpose IoT platform based on a combination of Low-power Wireless Personal Area Network (LoWPAN) and multi-hop Wireless Sensor Network (WSN) technology. It supports reliable and guaranteed real-time data dissemination and analysis, as well as actuator control, in dynamic and challenging infrastructure-less environments. In this paper, we present the IoT platform architecture and an initial hard- and software prototype. Moreover, a use case based on real-time monitoring and training adaptation for cyclists is presented. Based on this case study, evaluation results are presented that show the ability of the proposed platform to operate under challenging and dynamic conditions.**

I. INTRODUCTION

The Internet-of-Things (IoT) paradigm is rapidly maturing, with many massive deployments in areas such as smart cities, home automation, and agricultural monitoring. These massive IoT applications require scalable low-power connectivity over a long range. Recently, there has been a rising demand for IoT in more critical sectors, such as health care, security, energy and industrial automation. They are referred to as mission-critical IoT applications, and additionally require specific Quality-of-Service (QoS) guarantees in terms of latency, throughput or reliability.

Current IoT deployments generally use Low-Power Wide Area Network (LPWAN) or cellular technologies (e.g., LoRa, Sigfox, NB-IoT, GPRS) to provide (low-power) connectivity to sensors and actuators. However, such solutions require an (often public and operator-managed) infrastructure of base stations or access points with sufficient coverage. This makes them highly suitable to provide low-cost best-effort connectivity in easily accessible urban environments. However, in rural or remote areas, this infrastructure is not always present. Moreover, these technologies generally do not support QoS differentiation.

Low-power Wireless Personal Area Network (LoWPAN) and Wireless Sensor Network (WSN) technologies, such as IEEE 802.15.4, are far more suited for such challenging environments, as they can provide infrastructure-less long-range connectivity over multiple hops. Several recent amendments have been made to the 802.15.4 standard to improve its suitability for IoT. IEEE 802.15.4e proposes an enhanced MAC layer based on Time-Slotted Channel Hopping (TSCH) that greatly increases reliability and efficiency in difficult and dense settings, such as industrial environments. IEEE 802.15.4g proposes a PHY amendment for sub-1GHz operations, which greatly increases the range of a single hop from dozens to hundreds of meters, and improves energy efficiency. The combination of IEEE 802.15.4e and g therefore has the potential to enable long-range low-power multi-hop connectivity with reliability and QoS guarantees in challenging and remote areas.

In this paper, we propose an end-to-end IoT platform for real-time sensor data dissemination and analytics, as well as actuator control in challenging and remote areas. It builds upon IEEE 802.15.4e and g to provide multi-hop long-range connectivity between sensors and data sinks. The TSCH MAC scheduler is optimized to significantly reduce latency to support real-time data analytics. Moreover, the platform provides multi-modal communication with Bluetooth Low Energy (BLE) and ANT+ to support the connection of a variety of wireless sensors and actuators. Finally, integrated distributed data analytics features support real-time network-aware data processing either inside the network or in the cloud back-end when an Internet connection is available. In order to exemplify the benefits of the platform, we present a real-life case study. It offers a real-time data-driven cycling experience, where amateur or professional cyclists wear a set of sensors. This allows intelligent agents or coaches to monitor them and provide real-time feedback and continuous training adaptation. Evaluation results based on a prototype implementation of the platform show its advantages for challenging IoT environments.

The remainder of this paper is organized as follows. Section II presents related work in the area of IoT data dissemination and analytics platforms. Section III introduces the proposed IoT platform for real-time data dissemination and analytics in challenging areas. Subsequently, Section IV introduces a representative cycling monitoring and training adaptation use case on which the prototype implementation was applied. The preliminary prototype and initial evaluation results are presented in Section V. And finally, Section VI presents future research challenges and our conclusions.

II. RELATED WORK

This section presents related work in two related IoT areas: (i) providing low-power connectivity for real-time data dissemination in challenging environments, and (ii) performing real-time data analytics on top of such a dissemination platform.

A. IoT Connectivity in Challenging Environments

Most of the research on IoT platforms is focused on Smart Cities, where non-resource constrained networks monitor or control city assets [1], [2], [3]. Usually these approaches are based on wireless technologies that are highly dependent on a dense infrastructure of interconnected base stations and are therefore not suitable for rural, remote and challenging areas.

On one hand, as a potential solution, using long-range LPWAN or cellular technologies for providing rural connectivity has been proposed by several researchers [4], [5], [6]. Examples include the use of traditional mobile networks (e.g., GPRS, LTE), NarrowBand-IoT (NB-IoT) [7], LoRa, and SIGFOX. Due to the high range of tens of kilometers of such technologies, these solutions can rely on a very sparse infrastructure of base stations attached to a high-speed back-haul network. While NB-IoT offers the best QoS, LoRa and SIGFOX are technologies usually used only for low-throughput and delay tolerant applications. These technologies have the disadvantage that deploying and maintaining base stations is expensive and extending the network infrastructure to increase coverage is only economically viable if enough potential customers are present in the area. Rural, remote and challenging environments with low population density are therefore not profitable and will often not have (sufficient) coverage.

On the other hand, infrastructure-less approaches have been presented [8], [9], [10]. These approaches generally extend coverage through inexpensive multi-hop or meshing protocols. The technologies used can vary from broadband solutions such as Wi-Fi to low-power multi-hop WSN technologies such as DASH7 [11], Zigbee [12], and more recently IPv6 over the TSCH mode of IEEE 802.15.4e (6TiSCH) [13].

In this paper, we propose a hybrid solution that combines the advantages of infrastructure-based and infrastructure-less low-power connectivity for IoT in a single multi-modal platform. It employs an ad-hoc sub-1GHz wireless multi-hop network for providing end-to-end connectivity between sensor devices and the sinks. For this purpose, 6TiSCH together with IEEE 802.15.4g is used, enabling low-power, long-range, and reliable data dissemination. Moreover, a variety of LoWPAN technologies (e.g., BLE [14] and ANT+[15]) are provided by each device to connect a plethora of heterogeneous sensors and actuators. Using BLE, the sink device can connect to a smartphone or tablet, which in turn provides Internet connectivity and cloud synchronization using Wi-Fi or LTE whenever they are available. The proposed multi-modal platform provides a highly versatile IoT solution for challenging environments compared to state of the art solutions, with infrastructure-less data dissemination, sporadic disruption-tolerant Internet uplink, and support for heterogeneous wireless sensors and actuators.

B. Real-time Data Analytics for IoT

Semantic web technologies are often adopted to consolidate the heterogeneous and voluminous IoT data streams and expose them to the data analytics components in a uniform manner [16], [17]. They impose a common data representation, make the properties of the device and the context in which the data was gathered explicit and enable the straight-forward integration with background knowledge, e.g., the medical profile of patients or the layout of a smart city. Semantic reasoning enables to derive actionable insights out of this interlinked data, e.g., the light in a room is too bright for a patient with concussion. Several semantic IoT middleware frameworks have emerged to enable (real-time) semantic data annotation and support the development of data analytics components based on this enriched data [18], including Sense2Web [19], XGSN [20], [21], and SOFIA2 [22]. However, most of them assume centralized processing of the data in the cloud. They do not take into account the support for real-time local decision making for critical applications in which Internet connectivity and resources might be sparse. In contrast, we propose a solution that provides real-time distributed reasoning and data analytics inside the network, in combination with sporadic cloud-based offloading.

III. IOT PLATFORM FOR CHALLENGING ENVIRONMENTS

In this section, an end-to-end IoT platform for real-time sensor data dissemination and analytics, as well as actuator control in challenging and remote areas, is presented. Examples of such harsh environments include mountain trails or sparsely populated rural areas which lack static cellular infrastructure or other long-range IoT technologies, such as GPRS, LTE, NB-IoT, LoRA, or SIGFOX. We target dynamic network scenarios in which IoT devices are attached to mobile assets (e.g., vehicles, bicycles, or animals). In many such use cases the platform has to support real-time data dissemination among up to hundreds of power-constrained, wireless nodes in a limited geographical area, which all contend for the same wireless spectrum. A schematic representation of the proposed platform to handle these challenges is presented in Figure 1. The remainder of this section describes the different components of this platform.

A. Device Functionality

The platform will contain two types of devices that each have specific tasks: nodes and sinks. Platform nodes feature sensors and actuators, disseminate collected data and can

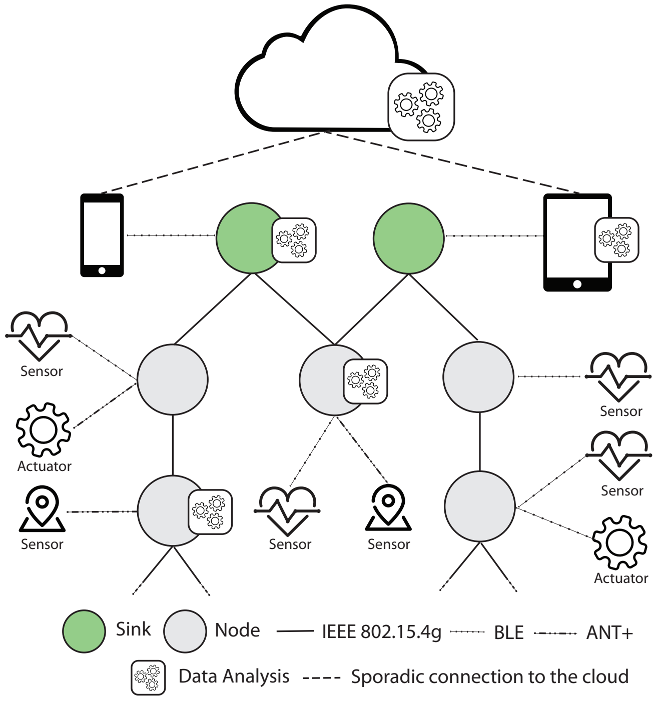


Fig. 1: An example of the IoT platform with sensors and actuators attached to mobile devices connected to one or more sinks over multiple hops, distributed data analytics components that provide real-time analysis, actuator feedback and visualization (through a connected smartphone or tablet). Sporadic cloud uplink is also provided through a connected smartphone or tablet device.

perform elementary data processing. Platform sinks receive monitored data from the network and provide almost instant feedback to the individual nodes after applying advanced data analytics.

1) Platform node: The functionality of an individual node in the network is threefold, as seen in Figure 1. First, it connects to both sensors (e.g., heart rate sensor or GPS tracker) and actuators that, respectively, send periodically captured data to the node and respond to received feedback from a data analytics unit in the network. Second, it is also responsible to relay monitored data towards the platform sinks and receive data coming from those sinks, using a multi-hop path as further explained in Section III-B. Third, it features elementary data processing capabilities that can provide real-time feedback to users or to actuators.

An important requirement is low-power consumption as these platform nodes are typically designed to be very small to avoid being a burden to the carrier. To be energy-efficient, only (ultra) low-power wireless protocols designed for forwarding sensor data, such as ANT+ or BLE, are considered. Also, wired connectivity is supported. However, this is often physically inconvenient or simply not feasible.

2) Platform sink: The platform sink receives the collected data from the network nodes and can responds with real-time feedback that will drive the actuators connected to the nodes. Therefore, the sink does not connect to any sensors itself, but is rather a collector of all monitored data or a subset of the data (as there can be multiple sinks in the network), as shown in Figure 1. The sink provides near-instant feedback to the nodes based on local data processing, data processing on a peripheral device, or in the cloud back-end when uplink connectivity is available. The connection between the sink and a peripheral device, such as a smartphone or tablet, can be any wireless protocol as the sink typically will have sufficient power resources compared to the other platform nodes (e.g., using Wi-Fi or BLE). The peripheral device can perform advanced data analytics on the received data and/or can use a visualization application to show the data to users. If available, cloud resources could also be used to analyze the data, but a steady Wi-Fi or 3G/4G connection is not guaranteed in challenging and remote environments and will rather be sporadic.

B. Data Dissemination

The platform should support the end-to-end dissemination of real-time data from sensors to the sink and in the reverse direction over a range of up to several kilometers, without relying on fixed network infrastructure such as 4G or LPWAN. Due to transmit power constraints and possible lack of line-of-sight between source and sink, end-to-end connectivity will require multi-hop communication, as shown in Figure 1. Therefore, a multi-hop network is set-up using the IEEE 802.15.4g physical layer in combination with the IEEE 802.15.4e MAC layer. This turned out to be the most promising solution after comparing different infrastructure-less and wireless candidate technologies (e.g., Wi-Fi, BLE, DASH7, and IEEE802.11ah). In terms of satisfying throughput and distance constraints, low-power operations and multi-hop support, it surpassed all other existing technologies. IEEE 802.11ah also seemed very promising but its current lack of hardware makes its use in the platform impossible. IEEE 802.15.4g is a recent PHY amendment to the IEEE 802.15.4 standard which supports an infrastructure-less mode and is specifically tailored for low-power long-range communication by using the 868 MHz band. Another advantage of the IEEE 802.15.4g physical layer is that it can be combined with the so-called 6TiSCH architecture that combines industrial performance in terms of reliability and power consumption with a full IPv6-enabled IoT upper stack [13]. Two important aspects of the 6TiSCH architecture, i.e., schedule management and routing, are discussed in more detail.

1) Schedule management: 6TiSCH uses the TSCH mode of the IEEE 802.15.4e MAC layer which combines channel hopping to avoid external interference and multi-path fading with a TDMA-based schedule that allows network nodes to be extremely energy-efficient and reliable. The tight time-synchronized TX/RX schedule avoids battery power waste by allowing nodes to turn their radio off and only turn it on when they are expected to send or receive data during a specified time slot. A scheduling algorithm is responsible for the management of this schedule by intelligently assigning

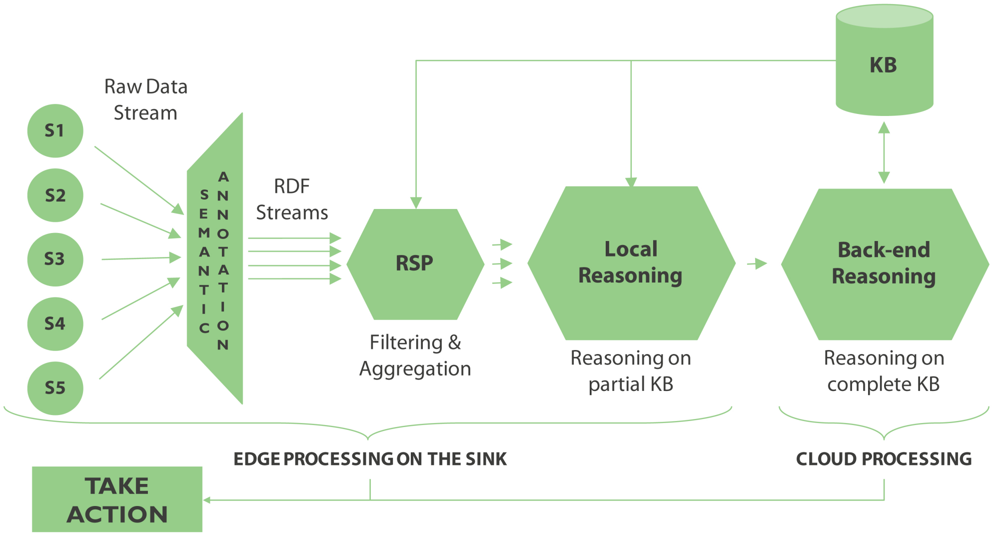


Fig. 2: Cascaded reasoning pipeline to enable real-time semantic reasoning within environments with sparse Internet connectivity and limited local resources.

available time-frequency resources to nodes that have data ready for transmission.

The 6TiSCH Working Group (WG) is standardizing a scheduling function called Scheduling Function Zero (SF0) which dynamically adapts the number of reserved time slots between neighbor nodes, based on the currently allocated bandwidth and the requirements of a node's neighbors [23]. SF0 however performs no intelligent allocation of specific time slots: it picks its time slots randomly which can lead to suboptimal latency results. A more intelligent approach of scheduling time slots is used by the Low Latency Scheduling Function (LLSF) which daisy-chains receiving and transmitting time slots in a multi-hop path in order to decrease the latency [24]. We implemented an enhanced version of LLSF, called Enhanced Low Latency Scheduling Function (eLLSF) that explicitly differentiates between reserving time slots to a parent or to a child, a feature that was not discussed in the original work on LLSF. When eLLSF reserves multiple TX time slots to a parent, it will distribute these time slots evenly among the reception slots (with the so-called *largest gaps* between the reception and transmission slot) of all the children. If not all time slots can be distributed evenly, the remainder of the time slots is allocated randomly to the children. When reserving a time slot to a child, the original three-step reservation process of LLSF is used.

2) Routing: To route the data throughout the network to the appropriate sinks, the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) is used [25]. RPL was specifically designed to face the typical challenges of WSNs i.e., minimizing energy consumption and latency while still satisfying multiple network constraints. In RPL, each network topology is organized as a tree, called a Destination Oriented Directed Acyclic Graph (DODAG). Multiple DODAG instances can exist in a single network, relaying data to different sinks based on different parameters. This allows the platform to have multiple sinks and route (different subsets of) the collected data to multiple sinks.

C. Real-time Data Analytics

The proposed platform combines stream reasoning with the cascading reasoning paradigm [26] to support real-time data analytics for critical applications that deal with limited local resources and sparse Internet connectivity. Stream reasoning [27] focuses on the scalable and efficient adoption of Semantic Web technologies for streaming data [28]. Recently, the first prototypes of RDF Stream Processing (RSP) engines [29] have emerged (e.g., C-SPARQL, CQELS, EP-SPARQL and SPARQLStream). They define a window on top of the stream and allow the registration of semantic queries which are continuously evaluated as data flows through the window. As such, these prototyped RSP engines can filter and query a continuous flow of data and can provide real-time answers to the registered queries.

As shown in Figure 2, the real-time data analytics consist of a processing hierarchy of reasoners that exploit the trade-off between the complexity of the reasoning and the velocity of the data stream. At the edge of the network (i.e., on the sink or a connected smartphone/tablet) a first filtering and aggregation is performed on the high frequency data stream by combining an RSP engine with one or more (traditional) semantic reasoners. The local reasoning can be performed more efficiently as it is done using a partial knowledge base (i.e., only the background knowledge that is applicable to that particular node and the devices connected to it). This enables local decision making to rapidly act on events occurring in the environment. It also reduces the volume and rate of the data, as only the aggregated conclusions are forwarded to the cloud, whenever Internet connectivity allows it. In the cloud, more complex reasoning can then be performed that combines conclusions derived by different edge nodes. As the data is processed close to its source, this results in reduced network congestions, less latency and improved scalability.

IV. USE CASE DESCRIPTION

The IoT platform presented in Section III was evaluated using a realistic use case in collaboration with industrial partners, in the context of the Flemish ICON CONtinuous Athlete MOnitoring (CONAMO) project. It encompasses real-time collection and analysis of athlete data during collective cycling. The goal of the use case is to improve the cycling experience of a group of cyclists by providing them with personalized insights in their performance.

Currently, data of cyclists, such as hearth rate, speed, power, cadence, is captured by a multitude of devices and apps like the ones offered by Garmin or Strava. These allow the publication of the results of a ride after the event, but do not allow real-time sharing of the data in environments where no adequate cellular connectivity is available, which is often the case at popular cycling trails (e.g., in the mountains). Several target groups will be able to profit from a solution which offers a real-time data-driven cycling experience. There are on one hand the professional cycling teams, where coaches will be able to see live performance indicators of their team members, which they can then use to adapt training sessions or to take strategic decisions during competition. But also during amateur cycling events, receiving performance feedback or updates about a friend's position might enable friendly competitions and transform cycling into a social experience.

Because of the nature of the use case, it requires many of the features the presented IoT platform aims to realize. Each individual bike is equipped with a node device that captures the data of the sensors attached to the cyclist and the bike. This data is then sent to the sink nodes, which will typically be the team cars or motorcycles from press and jury. It is clear that this network of platform and sink nodes is highly dynamic. The multi-hop approach of the platform to forward the data to the sink nodes is therefore needed because the distance between a cyclist and a sink node might be larger than the distance that can be bridged by a single-hop transmission.

Figure 3 shows both the distances between cyclists and sink points for an actual Tour De France stage (stage 20 Alpe d'Huez on July 25, 2015), for the first 50 cyclists and the sink points (i.e., team cars and press motorcycles) in between them. All distances are relative to the first cyclist. As the figure illustrates, there are sometimes large gaps of up to $660\,\mathrm{m}$ between the sink points (e.g., between $1.4\,\mathrm{km}$ and $2.1\,\mathrm{km}$), and in between these gaps there are cyclists for which the distance to the nearest sink is several hundred meters. In a training session of a professional team there will typically be less sink points than in an actual race, and during amateur cycling events the distances between cyclists are typically larger because of bigger variations in the performance of individual cyclists.

Because of specifics of cycling trails (presence of hills, mountains, trees, etc.) and low transmit power settings due to battery constraints, the transmission range between two nodes is expected to be at most a few hundred meters when using IEEE 802.15.4g. So even with a multi-hop approach, cyclist dynamics may cause certain nodes to temporarily become completely disconnected from the network, motivating the need for a disruption-tolerant routing protocol.

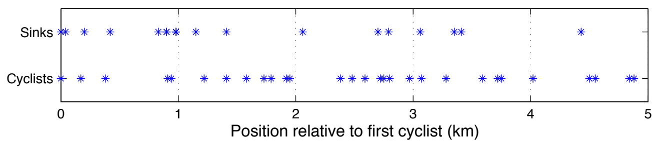
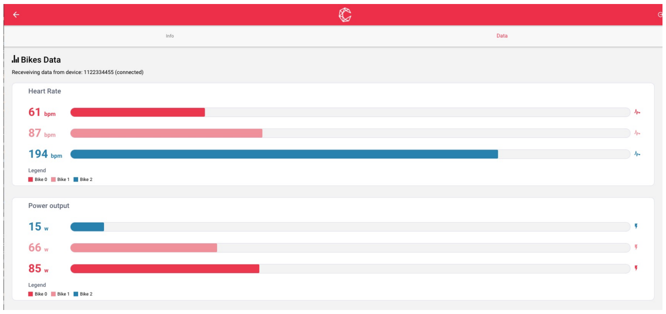


Fig. 3: Position of cyclists and sink points (cars and motorcycles) in an actual Tour de France stage.



Receveiving data from device: 1122334455 (connected)

Fig. 4: Screenshot from the CONAMO visualization app, showing hearth rate and power output data collected from three bikes.

Once the data of a cyclist has reached the sink node, it can be visualized, for example on the tablet of the coach in the team car. Figure 4 shows a screenshot of a prototype visualization app built in the context of the CONAMO project.

In order to provide real-time feedback about the on-going training or ride to the cyclist or coach in a personalized and context-aware fashion, the real-time data analytics part of the platform needs to intelligently, automatically and dynamically interpret the available data. The data set available to base the feedback on can be very heterogeneous. There is the stream of sensor data collected by the heterogeneous sensors on the bikes and cyclists, but also contextual information such as the route or weather and historical data known from each cyclist can be taken into account. As the data analysis solution will need to provide feedback to several cyclists at the same time, it needs to be highly scalable.

V. PROTOTYPE & RESULTS

This section describes the prototype of the presented platform, as developed in the context of CONAMO. The different hardware components and their interaction are discussed. Also, preliminary results involving the usage of IEEE 802.15.4g and the eLLSF scheduling function are shown.

A. *CONAMO Prototype*

The prototype device, as shown in Figure 5, consists of three major hardware components: a component responsible

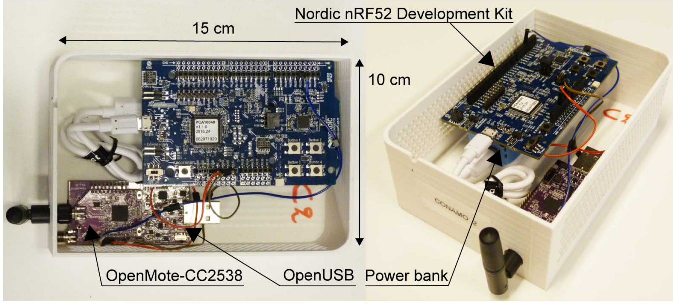


Fig. 5: The prototype device that can serve both as node and sink, containing an OpenMote-CC2538 and OpenUSB combination for the multi-hop connection, a Nordic nRF52 development kit board to connect to peripheral devices and a power bank that serves as the energy source of the device.

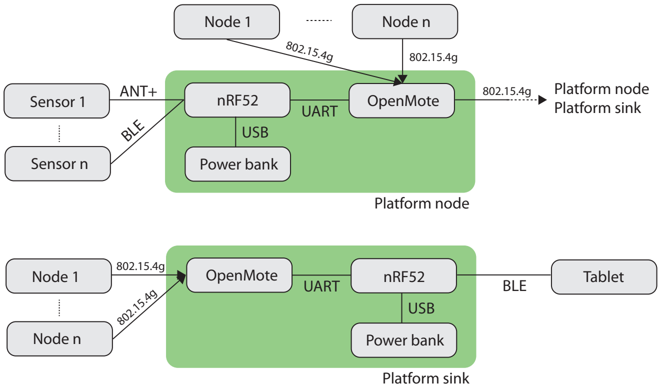


Fig. 6: The prototype components and their interaction in both a platform node and a platform sink.

TABLE I: Simulation parameters.

Parameter	**868 MHz values**	**2.4 GHz values**
Traffic generated (per node)	1 packet/s	1 packet/s
Packet size	51 bytes	127 bytes
Modulation	2FSK	OQPSK
# Channels	2	16
# Nodes	32	32
Experiment iterations	20	20

for the multi-hop IEEE 802.15.4g connection, a board that connects to other peripheral devices such as sensors and tablets and a commercial off-the-shelf power bank that serves as an energy source for the other two components. The different components and their interaction are shown in Figure 6.

1) Multi-hop connectivity: To set up the IEEE 802.15.4g multi-hop network, the prototype uses OpenMote hardware, which was specifically designed to support full IoT stack implementations [30]. More specifically, the prototype uses the OpenMote-CC2538 board that carries the CC2538 system-on-a-chip (SoC) combined with the OpenUSB board, shown in Figure 5 [31]. While the OpenMote-CC2538 contains a 32 MHz micro-controller and a IEEE 802.15.4-compliant 2.4 GHz radio, the OpenUSB is equipped with the CC1200 radio chip that operates on the 868 MHz band. As such, our prototype supports dual band operations in both frequency bands. Currently, the OpenMote component in the prototype is only used for upstream data traffic towards the sink. Future improvements will extend the prototype functionality to also support downward traffic (e.g., for real-time actuator control based on data analytics conclusions).

2) Peripheral connectivity: For the BLE and ANT+ connection with sensors, actuators, smartphones and tablets, we use the Nordic nRF52 development board [32]. It is equipped with the multi-protocol nRF52832 SoC that is targeted specifically at ultra-low power applications. This SoC supports BLE, ANT+, IEEE 802.15.4 and proprietary 2.4 GHz protocols.

Platform nodes use BLE and ANT+ to connect to sensors, as seen in Figure 6, as both protocols support low-power operation and are widely supported by various commercial sensing hardware. Meanwhile, a sink uses only BLE to connect to tablets or smartphones, which can display the collected data using a visualization application.

B. *IEEE 802.15.4g Network Evaluation*

In order to assess the ability and limitations of the 802.15.4g multi-hop network, this section presents preliminary results on its performance. The results compare network operations in the 868 MHz and the 2.4 GHz frequency bands and show the advantages of intelligent scheduling of transmission cells in 6TiSCH in terms of packet delay. The experiments are conducted using the open-source 6TiSCH simulator[1] developed by the 6TiSCH community. The simulator natively supports TSCH mode of the IEEE802.15.4e MAC layer and the RPL routing protocol. The simulation parameters are listed in Table I.

1) Frequency band evaluation: Figure 7 shows the Received Signal Strength Indicator (RSSI) value for both the 868 MHz and 2.4 GHz band as a function of the distance between transmitter and receiver. The sensitivity levels represent the lowest input signal the receiver can decode with an acceptable signal quality. We differentiate between the actual and the practical sensitivity levels. The former one is the one advertised in the data sheets of the radio chips and should be regarded as a *theoretical* optimal value. The latter is a value measured by the manufacturer (i.e., Texas Instruments[2]) in a practical setting and thus represents a more realistic estimate. The results clearly show that operation under 868 MHz supports a higher quality signal over a longer distance, i.e., up to 700 m compared to 90 m in the 2.4 GHz band (when comparing to practical sensitivity levels).

When looking at the total energy consumption, as shown in Figure 8, the results for both bands are very similar. While the absolute power consumption values for transmitting and receiving with the CC1200 radio chip in 868 MHz are in

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[1] 6TiSCH simulator: https://bitbucket.org/6tisch/simulator/src

[2] Texas Instruments Range Estimation Excel Sheet: http://e2e.ti.com/cfs-file/__key/communityserver-discussions-components-files/156/Range-Estimation-for-Indoor-and-Outdoor-Rev1_5F00_17.xlsm

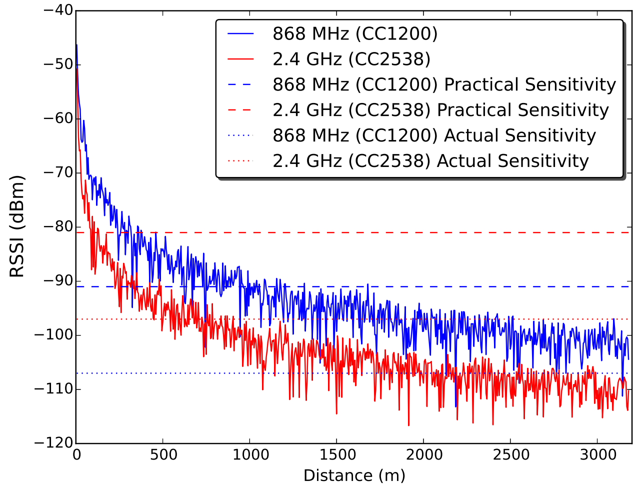

Fig. 7: RSSI value comparison between 868 MHz and 2.4 GHz IEEE 802.15.4g operation in function of the distance between two nodes.

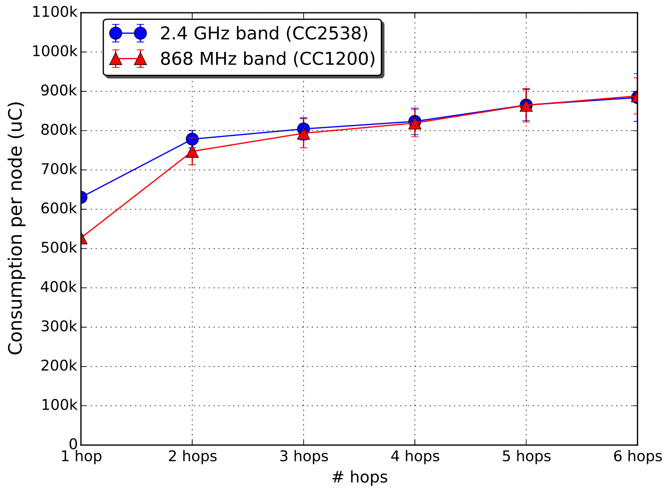

Fig. 8: Power consumption comparison between 868 MHz and 2.4 GHz IEEE 802.15.4g operation for a different number of hops.

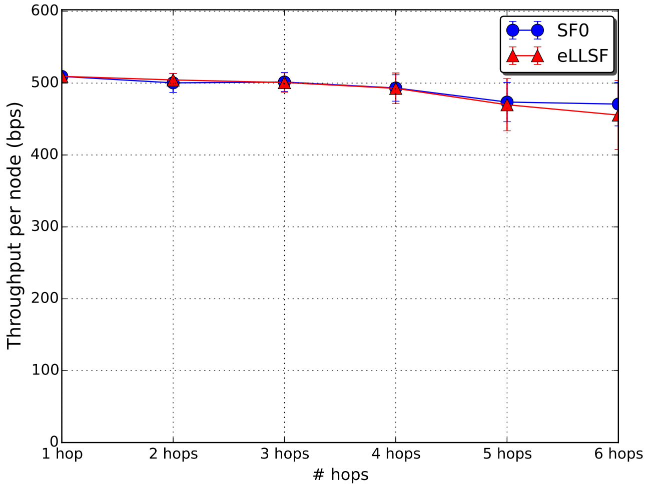

Fig. 9: Throughput comparison for a different number of hops between SF0 and eLLSF.

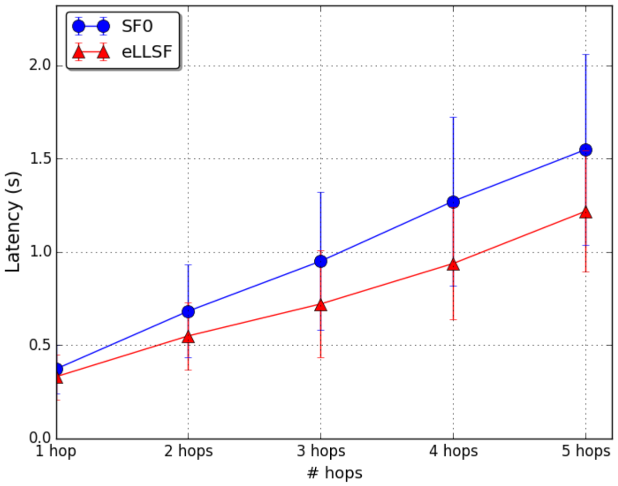

Fig. 10: Latency comparison for a different number of hops between SF0 and eLLSF.

theory higher, the RSSI of the links between hops is also better at this lower frequency. Better RSSI values result in a better packet delivery ratio which leads to less time slots needed to transmit each packet. This results in slightly better to equal total energy consumption in the 868 MHz band as compared to 2.4 GHz.

2) Scheduling function evaluation: To evaluate how the intelligent allocation of time slots in a TSCH schedule affects performance, both latency and throughput are compared for SF0 and eLLSF in Figures 9 and 10. As expected, the throughput for both scheduling functions is very similar and gradually decreases with increasing number of hops. This decrease is due to the higher number of time slots being reserved when there are more hops, which leads to a higher collision rate resulting in a lower throughput. The latency results clearly show that eLLSF outperforms SF0: up to a decrease of 27% in latency when considering 5 hops. This is due to the daisy-chaining of receive and transmit time slots that allows faster forwarding of packets towards the sink, while SF0 allocates its time slots randomly.

VI. CONCLUSION

In this paper, we present a novel IoT platform that supports reliable and guaranteed data dissemination and analysis, as well as actuator control, in dynamic and challenging infrastructure-less environments. The architecture, a case study based on real-time monitoring and training adaptation for cyclists and an initial hard- and software prototype are described in detail. Evaluation results based on the presented prototype show the promising abilities of this new multi-hop-based IoT platform: (i) there is no additional power consumption overhead when operating in the 868 MHz band, (ii) the 868 MHz band increases single-hop distance from less than 100 up to 700 m, and (iii) the latency is significantly decreased when intelligently allocating time slots.

In the future, additional research will be done to develop a disruption-tolerant, dynamic variant of RPL, operating on top of IEEE 802.15.4g, which can deal with temporarily communication disruptions and a continuously-changing network topology. Also, an even more advanced TSCH scheduling function needs to be developed that further decreases the latency while taking the highly dynamic topology complexity of the considered scenarios into account.

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REFERENCES

[1] J. Lanza, L. Sánchez, V. Gutiérrez, J. A. Galache, J. R. Santana, P. Sotres, and L. Muñoz, "Smart city services over a future internet platform based on internet of things and cloud: The smart parking case," *Energies*, vol. 9, no. 9, p. 719, 2016.

[2] S. Latre, P. Leroux, T. Coenen, B. Braem, P. Ballon, and P. Demeester, "City of things: An integrated and multi-technology testbed for IoT smart city experiments," in *Smart Cities Conference (ISC2), 2016 IEEE International*. IEEE, 2016, pp. 1–8.

[3] J. Jin, J. Gubbi, S. Marusic, and M. Palaniswami, "An information framework for creating a smart city through internet of things," *IEEE Internet of Things Journal*, vol. 1, no. 2, pp. 112–121, April 2014.

[4] C. Pham, A. Rahim, and P. Cousin, "Low-cost, long-range open IoT for smarter rural African villages," in *Smart Cities Conference (ISC2), 2016 IEEE International*. IEEE, 2016, pp. 1–6.

[5] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," *IEEE Wireless Communications*, vol. 23, no. 5, pp. 60–67, 2016.

[6] S. Aust and T. Ito, "Sub 1GHz wireless LAN deployment scenarios and design implications in rural areas," in *GLOBECOM Workshops, 2011 IEEE*. IEEE, 2011, pp. 1045–1049.

[7] J. Gozalvez, "New 3GPP standard for IoT [mobile radio]," *IEEE Vehicular Technology Magazine*, vol. 11, no. 1, pp. 14–20, March 2016.

[8] I. Foche-Pérez, J. Simó-Reigadas, I. Prieto-Egido, E. Morgado, and A. Martínez-Fernández, "A dual IEEE 802.11 and IEEE 802.15–4 network architecture for energy-efficient communications with low-demanding applications," *Ad Hoc Networks*, vol. 37, pp. 337–353, 2016.

[9] Z. Zaidi and K.-c. Lan, "Wireless multihop backhauls for rural areas: A preliminary study," *PloS one*, vol. 12, no. 4, p. e0175358, 2017.

[10] J. Simo-Reigadas, E. Municio, E. Morgado, E. M. Castro, A. Martinez, L. F. Solorzano, and I. Prieto-Egido, "Sharing low-cost wireless infrastructures with telecommunications operators to bring 3G services to rural communities," *Computer Networks*, vol. 93, pp. 245–259, 2015.

[11] M. Weyn, G. Ergeerts, R. Berkvens, B. Wojciechowski, and Y. Tabakov, "DASH7 alliance protocol 1.0: Low-power, mid-range sensor and actuator communication," in *Standards for Communications and Networking (CSCN), 2015 IEEE Conference on*. IEEE, 2015, pp. 54–59.

[12] P. Kinney *et al.*, "Zigbee technology: Wireless control that simply works," in *Communications design conference*, vol. 2, 2003, pp. 1–7.

[13] P. Thubert, "An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4," Internet Engineering Task Force, Internet-Draft draft-ietf-6tisch-architecture-11, Jan. 2017, work in Progress. [Online]. Available: https://datatracker.ietf.org/doc/html/draft-ietf-6tisch-architecture-11

[14] *Bluetooth Core Specification*, The Bluetooth Special Interest Group, 2016.

[15] "This is ANT: the Wireless Network Solution," https://www.thisisant.com/, Accessed: 2017-04-21.

[16] C. Perera, A. Zaslavsky, P. Christen, and D. Georgakopoulos, "Context aware computing for the internet of things: A survey," *IEEE Communications Surveys and Tutorials*, vol. 16, pp. 414–454, 2014.

[17] P. Barnaghi, W. Wang, C. Henson, and K. Taylor, "Semantics for the internet of things: Early progress and back to the future," *Int. J. Semant. Web Inf. Syst.*, vol. 8, pp. 1–21, Jan. 2012.

[18] J. Mineraud, O. Mazhelis, X. Su, and S. Tarkoma, "A gap analysis of internet-of-things platforms," *Computer Communications*, vol. 89–90, pp. 5–16, 2016.

[19] S. De, T. Elsaleh, P. Barnaghi, and S. Meissner, "An internet of things platform for real-world and digital objects," *Scalable Computing: Practice and Experience*, vol. 13, no. 1, pp. 45–58, 2012.

[20] J. Calbimonte, S. Sarni, J. Eberle, and K. Aberer, "XGSN: An open-source semantic sensing middleware for the web of things," in *Proc. of the 7th International workshop on Semantic Sensor Networks (SSN) at the International Semantic Web Conference*, 2014, p. 51.

[21] M. Ali, N. Ono, M. Kaysar, K. Grin, and A. Mileo, "A semantic processing framework for IoT-enabled communication systems," in *Proc. of the International Semantic Web Conference*, 2015, pp. 241–258.

[22] Indra, "SOFIA2: The first middleware for smart applications," http://sofia2.com/home_en.html, 2017.

[23] D. Dujovne, L. A. Grieco, M. R. Palattella, and N. Accettura, "6TiSCH 6top Scheduling Function Zero (SF0)," Internet Engineering Task Force, Internet-Draft draft-ietf-6tisch-6top-sf0-03, Mar. 2017, work in Progress. [Online]. Available: https://datatracker.ietf.org/doc/html/draft-ietf-6tisch-6top-sf0-03

[24] T. Chang, T. Watteyne, Q. Wang, and X. Vilajosana, "LLSF: Low latency scheduling function for 6TiSCH networks," in *2016 International Conference on Distributed Computing in Sensor Systems (DCOSS)*, May 2016, pp. 93–95.

[25] A. Brandt, J. Vasseur, J. Hui, K. Pister, P. Thubert, P. Levis, R. Struik, R. Kelsey, T. H. Clausen, and T. Winter, "RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," RFC 6550, Mar. 2012. [Online]. Available: https://rfc-editor.org/rfc/rfc6550.txt

[26] H. Stuckenschmidt, S. Ceri, E. D. Valle, and F. van Harmelen, "Towards expressive stream reasoning," in *Proc. of Dagstuhl seminar on semantic aspects of sensor networks*. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, Germany, 2010, pp. 1–14.

[27] E. Della Valle, S. Ceri, F. Harmelen, and D. Fensel, "It's a streaming world! Reasoning upon rapidly changing information," *IEEE Intelligent Systems*, vol. 24, no. 6, pp. 83–89, 2009.

[28] A. Margara, J. Urbani, F. van Harmelen, and H. Bal, "Streaming the web: Reasoning over dynamic data," *Journal of Web Semantics*, vol. 25, pp. 24–44, 2014.

[29] X. Su, E. Gilman, P. Wetz, J. Riekki, Y. Zuo, and T. Leppänen, "Stream reasoning for the internet of things: Challenges and gap analysis," in *Proc. of the 6th International Conference on Web Intelligence, Mining and Semantics (WIMS)*. ACM, June 2016.

[30] X. Vilajosana, P. Tuset, T. Watteyne, and K. Pister, "Openmote: open-source prototyping platform for the industrial IoT," in *International Conference on Ad Hoc Networks*. Springer, 2015, pp. 211–222.

[31] *Powerful Wireless Microcontroller System-On-Chip for 2.4-GHz IEEE 802.15.4, 6LoWPAN, and ZigBee Applications*, Texas Instruments, 12 2012, rev. April 2015.

[32] "nrf52 dk: Development kit for nrf52832," https://www.nordicsemi.com/eng/Products/Bluetooth-low-energy/nRF52-DK, Nordic Semiconductor, Accessed: 2017-04-21.