Towards collective hyperlocal contextual awareness among heterogeneous RFID systems

Jeffrey Dungen, Juan Pinazo Neto
reelyActive
Montréal, Québec, Canada
Email: jeff@reelyactive.com, juan@reelyactive.com

Abstract*—Until recently, cases of independently operated radio frequency identification (RFID) deployments occupying a common space could be considered rare. However, the recent emergence of the RAIN Alliance and Bluetooth Low Energy (BLE) is resulting in the proliferation of fixed and mobile infrastructure for the radio-identification of both things and people through standardised passive and active RFID technologies, respectively. Consequently, today, there are everyday situations where independently operated RFID systems are likely to co-exist, both ephemerally and indefinitely. In this paper, we present a mechanism for mutual discovery and the subsequent exchange of structured data among such colocated, and often heterogeneous, systems. The resulting machine-readable real-time representation of the real-world on a human scale is what we call hyperlocal context, an open, standards-based language for the Internet of Things. We argue that hyperlocal context and the presented mechanisms foster efficient crowd-sensing which combines the complementary characteristics of both active and UHF passive RFID systems. The underlying framework has been successfully implemented in open source software with BLE supported and UHF passive RFID integration in progress. Collaboration among the scientific and industrial communities to advance standards for collective context will only become more critical as the proliferation of RFID infrastructure accelerates.

I. Introduction

The Internet of Things (IoT) may be defined as the understanding, by computers, of the real world in real time, without the need for human-entered data. Said differently, the IoT is about computers understanding both the spatio-temporal and semantic relationships among physical *things*, as life unfolds. The aforementioned definition was offered by Kevin Ashton, ten years after he coined the phrase in 1999, while working at the MIT Auto-ID lab [1]. At that time, passive radio-frequency identification (RFID) promised to be a key enabling technology for the IoT.

For the fifteen years following, widespread adoption of RFID technologies surely lagged behind the ambitions of the early proponents of the IoT. Nonetheless, in 2014, two significant milestones were reached. First, a group of key stakeholder companies formed the RAIN RFID Alliance [2] which promises interoperability of hundreds of billions of long-range (up to approx. 12m) ultra-high frequency (UHF) passive RFID tags and readers. And, second, Bluetooth Low Energy (BLE) attained sufficient traction to become, arguably [3], the first global standard for active RFID, it too promising interoperability and a detection range on the order of tens of metres.

While RFID technologies are catalysts of the notion of a *physical* web, in a separate sphere, but over roughly the same timeline, the *semantic* web had lived a similar story. In 2014, coincidentally, JSON-LD, a popular enabling standard, became a W3C recommendation [4]. Today, combined with Schema.org, it is championed by industry giants such as Google as the preferred means for representing *things*, including, incidentally, the growing number of people, products and places identified and tracked using RFID technology.

Each of the three aforementioned technologies has achieved independent success. UHF passive RFID is notably used for real-time inventory, leveraging dedicated reader infrastructure. BLE has instead adopted a mobile-centric approach due to its widespread adoption in smartphones, which today represent no fewer than 3.2 billion smart edge devices, a number expected to double by 2021 [5]. And JSON-LD is commonly used by online search engines. In this paper we will argue that the three could, and should, complement one another in the context of IoT, to further the understanding of the real world in real time.

First we present the common characteristics of RFID-based real-time location systems (RTLS) which support the endeavour. We then present the concept of structured, linked data to associate semantic meaning to RFID/RTLS data. Next we combine identity, location and structured data to introduce the concept of hyperlocal context, and present a standards-based mechanism for spontaneous, collective crowd-sensing among independent RFID platforms. Finally, we conclude with practical, real-world applications under exploration and provide recommendations for ongoing development.

II. Real-Time Location

RFID technology, both active and passive, enables the unique identification of devices at a distance by readers. When a reader (which we will instead refer to as *receivers* throughout this paper) receives the radio packet from the identified device, the collected information comprises of:

- the identifier (and any additional payload) of the device
- the identifier of the receiver itself
- the time of reception
- the received signal strength indication (RSSI)

The RSSI provides at least a coarse approximation of the distance between the device and the receiver at the time of packet reception. As a result, both active and passive RFID

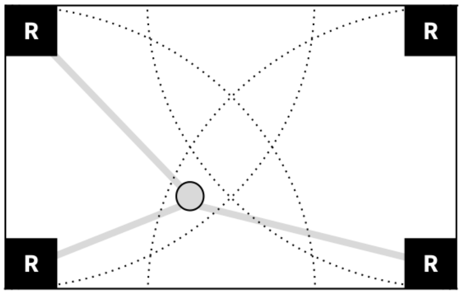

Fig. 1. Infrastructure-based radio-location with four fixed receivers (R), with read range delimited by dotted lines. One identifiable device is shown.

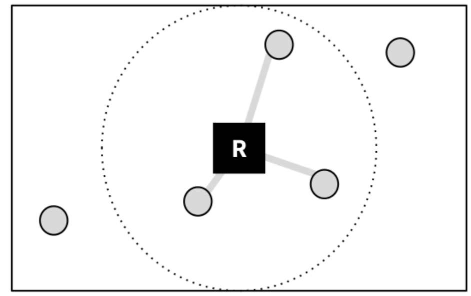

Fig. 2. Radio-location by mobile receiver (R), with read range delimited by dotted line. Five identifiable devices are shown.

systems further an understanding of spatio-temporal relationships between physical *things*. In the case of BLE and UHF passive RFID, expected read ranges in real-world deployments are typically on the order of metres, which corresponds to a human scale of awareness. In other words, an individual receiver's "sense of local" is similar to that of a human.

As mentioned in the introduction, passive RFID systems currently tend toward an infrastructure-centric approach while BLE adoption favours a mobile-centric approach. Given that both approaches and technologies are increasingly likely to coexist, we present the complementary characteristics of each with respect to collective contextual awareness.

A. Infrastructure-Centric Radio-Location

Figure 1 illustrates an infrastructure of fixed receivers within a physical space. This configuration essentially answers the question *where are the devices within my space?* Fixed infrastructure typically benefits from ample, reliable power and connectivity, which affords the continuous radio, communication and computation activity necessary for optimal real-time location at the edge. While this especially suits the needs of passive RFID readers, it is equally useful for active systems as we at reelyActive have argued in the past [6], and indeed commercial BLE real-time location systems (RTLS) include [7] and [8]. Moreover, it is possible that recent consumer products such as smart televisions and set-top boxes which benefit from power, connectivity and a BLE radio will overtake, if they have not done so already, enterprise receiver infrastructure in terms of both numbers and distribution.

B. Mobile-Centric Radio-Location

Figure 2 illustrates a mobile receiver discovering devices within range. This configuration essentially answers the question *what devices are near my current location?* Mobile receivers benefit from the ability to move coverage where and when it is needed, albeit on a constrained power, computation and connectivity budget. In the case of a smartphone, it affords a human user an understanding of their immediate surroundings. Handheld UHF passive RFID readers offer the same benefit, while mobile robots and drones extend these capabilities without the need for a human operator.

III. Digital Representation and Association

In the previous section we presented means of automatic identification and location of devices. Here we first present how people, products and places (among other *things*) can be meaningfully represented using structured, linked data hosted on the web. We then present how these machine-readable representations can be associated with any radio-identifiable device.

A. Digital Representation

While the concept of say, a product, can be digitally represented in endless ways, in order to maximise widespread machine-readability, representation in a structured and linked data format is advisable. Structured data ensures a shared vocabulary, and hence a shared understanding. Linked data is a means of publishing the structured data so that it can be connected and queried. As mentioned in the introduction, JSON-LD [9] (the LD stands for linked data) was adopted by the W3C in 2014. The subsequent adoption of JSON-LD and Schema.org [10] (a structured data vocabulary) by Google represents, to the best of the authors' knowledge, the most promising candidate for widespread adoption.

```
{
  "@context": {
    "schema": "http://schema.org/"
  },
  "@graph": [
    {
      "@id": "product",
      "@type": "schema:Product",
      "schema:name": "BLE Reelceiver",
      "schema:manufacturer": {
        "@type": "schema:Organization",
        "schema:name": "reelyActive",
        "schema:url": "http://reelyactive.com/"
      },
      "schema:model": "RA-R436"
    }
  ]
}
```

The preceding listing illustrates the representation of a product, in this case reelyActive's own BLE receiver, using JSON-LD and Schema.org, and would be hosted on the web at a given URL, for example [11]. The included manufacturer URL points to additional structured, linked data. To facilitate the manipulation of such data, we developed an online tool [12].

Fig. 3. Raw BLE packet split into 48-bit identifier and Eddystone URL

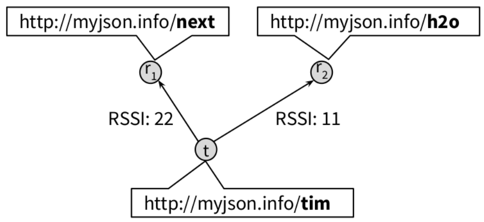

Fig. 4. Hyperlocal context

B. Digital Association

RFID technologies represent devices as identifiers. Structured data can be represented by a URL, as we have described. By associating device identifiers with structured data via a URL, computers gain the ability to understand the people and products (among other *things*) that they detect and locate in real-time. We cover this topic extensively in our 2015 paper entitled "Low-Power Wireless Advertising Software Library for Distributed M2M and Contextual IoT" [13]. In the case of BLE, it is possible to directly embed a short URL alongside the device identifier, as illustrated in Figure 3, using the Eddystone protocol, a method for which we advocate. In the case of UHF passive RFID, RAIN promotes the use of the ISO/IEC 18000-63 and GS1 EPC UHF Gen 2 standards [15] which support digital association by a variety of means of lookup which require additional steps, but can achieve the same result.

IV. Real-Time Hyperlocal Context

In Section II we presented the automatic identification and location of devices on a scale of tens of metres. In Section III we presented the structured and linked representation of *things* and the means to associate these with any radio-identifiable device via a URL. The combination of the above is what we call hyperlocal context: a digital representation of the occupants of a space at a human scale. Hyperlocal context can be queried from either an infrastructure-centric view (*what is the context at the given space?*) or a mobile-centric view (*what is the context near the given receiver?*). In either case it is represented as a directed graph with receivers and devices as nodes, and edges as RSSI values. Additionally, each node is associated with an URL. A simple, illustrative example is shown in Figure 4 which corresponds exactly to the JSON listing that follows. If device "t" represents Tim Berners-Lee and devices "r1" and "r2" represent a NeXT Computer and the water cooler at CERN, respectively (each being a receiver), then the hyperlocal context could be interpreted by a computer to mean *Tim Berners-Lee is closer to the computer than to the water cooler*.

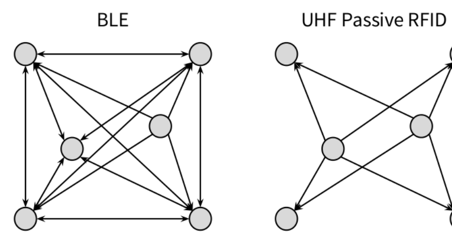

Fig. 5. Directed graph of radio-identification for both BLE and UHF passive RFID. Arrows point towards receivers.

```
{
  "devices": {
    "t": {
      "url": "http://myjson.info/tim",
      "nearest": [
        { "device": "r1", "rssi": 22 },
        { "device": "r2", "rssi": 11 }
      ]
    },
    "r1": {
      "url": "http://myjson.info/next"
    }
    "r2": {
      "url": "http://myjson.info/h2o"
    }
  }
}
```

Next we consider a more elaborate example which highlights key differences between BLE and UHF passive RFID technologies. Figure 5 illustrates, for each technology, an identical geometry of six devices. In the case of UHF passive RFID, it is easy to identify the readers in the four corners and the tags in the centre given the outwardly directed RSSI edges. In the case of BLE, because devices can be transceivers, enabling mutual identification, there are potentially far more directed RSSI edges.

Hyperlocal context represents location in relative rather than absolute terms (*what is close to what?*) which, given the human scale of read ranges on the order of metres, is amply sufficient for typical applications. Moreover, this limits the scale of the hyperlocal context data such that it can be computed and manipulated locally by resource-constrained edge systems, such as ARM and MIPS-based embedded computers, as we have successfully demonstrated [16].

If the absolute location of a device or receiver is specified in its structured data representation, this information can nonetheless be used to anchor the node to a true position. Frameworks for querying and traversing structured and linked data are outside of the scope of this paper, however relevant research includes [17] and related works by the same authors.

V. Collective Hyperlocal Context

In the previous section we defined hyperlocal context, which is a digital representation of the occupants of a space at a human scale, and which can be derived by any independent receiver. Now, given the increasing likelihood of a heterogeneous mix of RFID technologies coexisting in a space, be it as mundane as a friend's mobile phone in your connected home, or as commercially promising as correlated item and customer tracking in retail, we argue for a universal mechanism for mutual discovery and collective identification, location and representation, of which we present our current experimental candidate.

A. Motivation

From a technical perspective, the motivation for collective hyperlocal context is twofold. First, consider the inefficiency of the duplication of work by independent systems attempting to derive the same result. Especially for power and communication-constrained mobile devices, offloading and/or reducing discovery and computation effort is highly desirable. Second, consider the incompleteness of the hyperlocal context compiled by any individual system. By sharing the crowd-sensed information, the collective maximises the accuracy of the spatio-temporal and semantic understanding of all the radio-identifiable devices together they detect.

B. System Discovery

A discovery mechanism is required for independent systems to first acknowledge each other's presence before establishing a means to share information. As was illustrated in Figure 5, in the case of BLE, mutual discovery between nearby transceivers is in fact trivial. For instance, the mutual detection of a mobile phone and BLE receiver infrastructure is common in commercial applications (for methods see [18]). In the case, however, of passive RFID, the readers themselves are seldom intrinsically radio-identifiable. Of course, the proximity of multiple receivers could be inferred by their simultaneous detection of the same device, but to make such an inference implies that they must already share data. Arguably the simplest and most cost-effective means to make passive RFID and other non-BLE receivers radio-discoverable would be to equip them with an inexpensive BLE transceiver specifically for this purpose. In this case, the augmented receiver would advertise its unique identifier and URL, via Eddystone, to all other receivers in range. The augmented receiver could equally discover independent nearby receivers by listening using that same BLE radio. Figure 6 illustrates the identification directed graph of three independent systems both before and after implementation of the proposed discovery mechanism.

C. Context Discovery

The system discovery mechanism enables each coexisting RFID system to radio-identify the receivers of the others, and, in turn, to query their respective URLs for structured data. Said differently, the mechanism ensures that each receiver includes every other nearby receiver in its own hyperlocal context. Alone, this discovery mechanism represents no advancement over the current state of the art. However, if each receiver additionally shares its own hyperlocal context with its peers, the discovery mechanism is extended by one layer to include the devices detected by *all* peers. In other words, each receiver includes every other nearby receiver and the devices detected by *those* receivers in its own hyperlocal context.

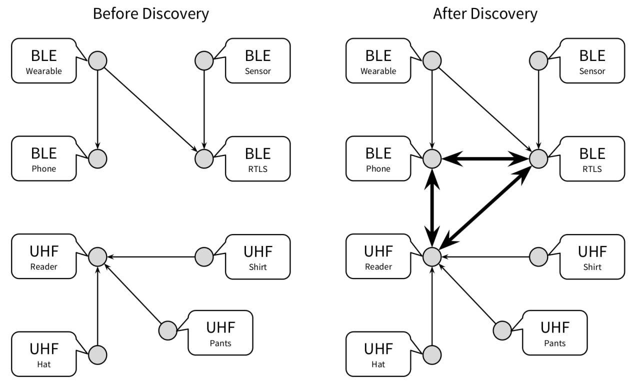

Fig. 6. Identification directed graph of smartphone, BLE infrastructure receiver and UHF infrastructure receiver. The emphasized edges are established with the proposed system discovery mechanism, assuming that the UHF receiver has been augmented with a BLE radio.

The mechanism to share hyperlocal context is simple. Each receiver (or agent acting on its behalf):

- serves its own hyperlocal context via another URL
- publishes this URL in its own structured data representation

We propose to name this new property "hyperlocalcontext". For example, if the hyperlocal context were served at http://www.hyperlocalcontext.com, it would suffice to add a "hyperlocalcontext" property to the receiver's JSON-LD representation:

```
{
  "@context": {
    "schema": "http://schema.org/"
  },
  "@graph": [
    {
      "@id": "product",
      "@type": "schema:Product",
      ...
    }
  ],
  "hyperlocalcontext": "http://www.hyperlocalcontext.com/"
}
```

The coexisting systems could therefore consume the hyperlocal context as JSON, such as the listing presented in Section IV, from that URL. To summarise, systems with BLE-capable receivers would:

- discover nearby receivers and their advertised URL
- fetch from those URLs each receiver's structured data representation (as JSON-LD)
- search for a "hyperlocalcontext" property in each
- consume hyperlocal context from each such URL

D. Collective Context

Following the context discovery procedure presented above, each system will possess its own individual hyperlocal context, plus a copy of each other discovered receiver's individual hyperlocal context. Each of these is a directed graph with zero or more device nodes connected to the single receiver node. Collective context is established by combining these, into a single directed graph.

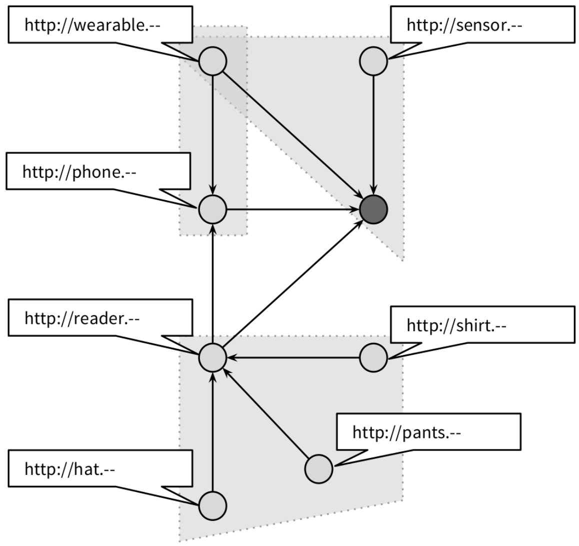

Fig. 7. Collective hyperlocal context of the situation presented in Figure 6, represented as a directed graph from the perspective of the darkened node. The three individual hyperlocal contexts are indicated with grey backgrounds.

Figure 7 illustrates the collective context established following the context discovery procedure, based on the situation presented in Figure 6. Edges directed out from the perspective (darkened) node may be omitted from the combination to avoid redundancy.

The example highlights several benefits of collective hyperlocal context. For instance, any system could estimate, by relative RSSI, whether the wearable is closer to the phone or to the perspective receiver. The active RFID systems become aware of the passive-tagged clothing items and the passive RFID system can track the mobile phone and read the active sensor data, if any.

To the best of the authors' knowledge, collective hyperlocal context represents a novel concept combining extended device discovery, semantic representation and relative real-time location across heterogeneous RFID technologies.

VI. Practical Applications

Collective hyperlocal context is relevant to any application in which independent RFID systems, with complementary purpose, coexist on a human scale. In this section we provide two illustrative examples which highlight the benefits of mutual access to complementary sensing capabilities and to extensive wireless coverage, respectively.

A. Retail Apparel

Consider two current trends in retail: item-level RFID tagging using RAIN, and indoor positioning of mobile devices through BLE. Each operates as an independent system. The former enables the retailer to track apparel items through the store, for example from the rack to the fitting room. The latter enables the shopper's smartphone to periodically position itself within the store. Neither system can, however, independently correlate the shopper's journey with the apparel items browsed: valuable information for both the shopper and the retailer.

Fitting the RFID readers with BLE radios, as prescribed in Section V, enabling them to advertise themselves, and hence their "hyperlocalcontext" URL, to the shopper's smartphone, collective hyperlocal context can thereby be established. As a result, the smartphone (likely instructed by a mobile application) can benefit by effectively asking the RFID readers about the items (*what apparel items are in the fitting room with me now?*), and said readers can benefit by polling the smartphone (or a server acting on its behalf) for its relative location (*where do you think you are in the store right now?*). The shopper obtains a useful history of the apparel items they browsed while the retailer gains valuable metrics from their in-store browsing behaviour.

An experimental implementation of this use case is in progress with ESG-UQAM [19], leveraging BLE and UHF RFID systems coexisting in their lab.

B. Building Automation

Consider the current proliferation of smart edge devices both in the home and in commercial buildings. It is not uncommon to find a heterogeneous mix of such systems in a modern building, for instance a smart television from one vendor, an IoT hub from another vendor, and, increasingly, connected lighting infrastructure from another vendor, each typically equipped with a BLE radio. A BLE wearable carried by a building occupant could be independently discovered and tracked by each system, limited to their respective areas of coverage.

Implementing the discovery mechanism presented in Section V, collective hyperlocal context can be established among the independent systems, as illustrated in Figure 8. Each would benefit from the additional coverage of the others, allowing discovery and tracking over a greater area. Moreover, if any one system were able to associate the wearable with a URL representing the occupant, the occupant's information could be accessed as structured data by the other systems. As a result, each system could understand and adapt to the user's preferences, improving comfort and/or efficiency.

An experimental implementation of this use case is currently in place at Notman House in Montreal, including 10 BLE receivers providing extensive coverage and collective hyperlocal context. Broader collective exchange is however limited by access to third-party vendors' APIs. Indeed, in the authors' experience, reluctance on the part of vendors to share their data may well be the greatest barrier to adoption of collective hyperlocal context at this time.

VII. Considerations for Ongoing Development

The concept of real-time hyperlocal context presented in Section IV has been successfully used in reelyActive production deployments for over three years while the mechanism of collective context presented in Section V remains experimental. Here we present the considerations for the ongoing development of collective hyperlocal context.

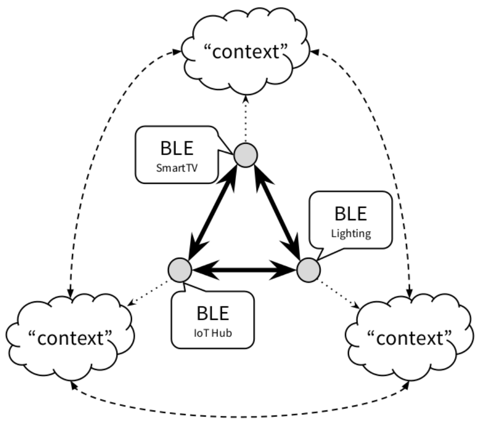

Fig. 8. Discovery and collective hyperlocal context of three independent but complementary systems. The emphasized edges represent the mutual device discoveries via BLE. The dashed edges represent the consumption of hyperlocal context over IP.

A. *Contextual data exchange over local network*

The URLs employed in the examples herein point to Internet-accessible servers, facilitating consumption by any Internet-connected device. In the case where coexisting systems have the ability to communicate over a local IP network, its use would be preferential in terms of efficiency and reliability. While outside of the scope of this paper, a promising such approach could leverage mDNS to additionally facilitate system discovery.

B. *Calibrated Radio Power*

The astute reader will note that the RSSI values presented herein are unitless. This is indeed intentional, as, in practice, we have found it difficult to reliably obtain calibrated RSSI values which, to be meaningful, require knowledge of the calibrated power of both receiver and transmitter. The Eddystone protocol which is key to the proposed discovery mechanisms nonetheless includes a one-byte calibrated transmission power field. Hyperlocal context should employ calibrated RSSI representation upon the establishment of general industry compliance.

C. *New and Evolving Radio Standards*

In December 2016, Bluetooth Version 5 was launched, notably creating a new advertising packet with significantly increased payload, enabling the transmission of longer Eddystone URLs. Because hyperlocal context is based solely on the core concepts of RFID, such evolution is accommodated by design. For the same reason, the emergence of a new RFID standard would be expected to have limited impact, if any, on the design.

D. *Security and Privacy*

Security and respect for privacy remain, for good reason, top priorities in the Internet of Things. The methods presented herein can and should be coupled with appropriate security measures and special attention should be accorded to the privacy implications of extended device discovery, as enabled by collective hyperlocal context.

VIII. Conclusion

The recent emergence of everyday situations where independent, yet complementary, RFID systems coexist creates extensive opportunities for the mutually-beneficial exchange of information to further a real-time machine-understanding of the real-world on a human scale. In this paper we have presented a mechanism for mutual discovery and the subsequent collective exchange of *hyperlocal context* data among such colocated systems. Both academic and commercial interests are free and encouraged to combine our open source software [20] with the presented methods to extend and improve the concept, apace with the proliferation of RFID and IoT technologies, as we continue to do ourselves in collaboration with partners representing both such interests. It is our hope that this work will contribute to a more open and connected Internet of Things which stands to benefit all of humanity.

References

[1] K. Ashton. "That Internet of Things Thing", RFID Journal, USA. [Online]. Available: http://www.rfidjournal.com/articles/pdf?4968

[2] "Welcome to RAIN RFID", RAIN RFID. [Online]. Available: http://rainrfid.org/

[3] "Advertise Yourself!", J. Dungen, reelyActive. [Online]. Available: http://www.slideshare.net/reelyActive/advertise-yourself-reelyactive-at-bluetooth-world-2014-59803555

[4] "JSON-LD 1.0", W3C. [Online]. Available: https://www.w3.org/TR/json-ld/

[5] "Ericsson Mobility Report 2016", Ericsson AB, Sweden. [Online]. Available: https://www.ericsson.com/mobility-report

[6] J. Dungen et al, "Towards a simple, versatile, distributed low-power wireless M2M Infrastructure", *2013 IEEE 38th Conf. on Local Computer Networks (LCN)*, Sydney, Australia, 2013, pp.890-895, 21-24.

[7] "Etusivu | 9Solutions", 9Solutions Ltd, UK. [Online]. Available: http://www.9solutions.com/

[8] "Quuppa | Do More With Location", Quuppa Oy, Finland. [Online]. Available: http://quuppa.com/

[9] "JSON-LD", W3C JSON-LD Community Group. [Online]. Available: http://json-ld.org

[10] "Schema.org", W3C Schema.org Community Group. [Online]. Available: http://schema.org

[11] "reelyActive RA-R436", reelyActive, Montreal, Canada. [Online]. Available: https://sniffypedia.org/Product/reelyActive_RA-R436/

[12] "jsonerator", reelyActive, Montreal, Canada. [Online]. Available: http://reelyactive.github.io/jsonerator/

[13] M.I. Jameel and J. Dungen, "Low-power wireless advertising software library for distributed M2M and contextual IoT", *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, Milan, Italy, 2015, pp. 597-602.

[14] "Eddystone", Google, USA. [Online]. Available: https://github.com/google/eddystone

[15] "Standards", RAIN RFID. [Online]. Available: http://rainrfid.org/resources/standards/

[16] "reelyActive DIY", reelyActive, Montreal, Canada. [Online]. Available: https://reelyactive.github.io/

[17] M. Lanthaler and C. Gütl, "On Using JSON-LD to Create Evolvable RESTful Services", *Proceedings of the 3rd International Workshop on RESTful Design (WS-REST 2012) at WWW2012*, Lyon, France, 2012, pp. 25-32.

[18] "diyActive: Integrate your Mobile App", reelyActive, Montreal, Canada. [Online]. Available: https://reelyactive.github.io/integrate-your-mobile-app.html#reelMobileHybrid

[19] "UQAM | Département de management et technologie", UQAM, Montreal, Canada. [Online]. Available: http://mantech.esg.uqam.ca/

[20] "hlc-server", reelyActive, Montreal, Canada. [Online]. Available: https://github.com/reelyactive/hlc-server