A Novel Cognitive IoT Gateway Framework: *Towards a Holistic Approach to IoT Interoperability*

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***Abstract*—While IoT devices and networks continue to scale in volume and heterogeneity across multiple application domains, they remain unconnected and the data generated from them remain largely inaccessible across the multiple application domains. This is due to a lack of holistic interoperability in the IoT enterprise. Various approaches have been used to address IoT interoperability but each approach only addresses different levels of interoperability in isolation. This paper presents a novel, hybrid approach to IoT interoperability that introduces cognition into the IoT gateway. Thus, the gateway, as a cognitive dynamic system, provides for holistic interoperability in an integrated manner.**

Keywords—IoT, Interoperability, Cognitive, Gateway

I. Introduction

The evolution of the internet over the last two decades, has given rise to an increasing demand for, and proliferation of fixed and mobile services. This increasing demand has fueled the quest for the next generation of broadband networks which are capable of meeting the exponentially increasing global human-user demand for more efficient mobile broadband communication services [1]. In addition to the expected large human-user profile for future networks, there is also a predicted explosion in broadband traffic emanating from various Machine Type Devices (MTDs), which are expected to leverage on Machine to Machine (M2M) communication/Machine Type Communication (MTC), and thus, engender the evolution of the true "Internet of Things (IoT)" paradigm [2]. Taking into account all kinds of possible sensors embedded in objects, and in infrastructure like buildings, vehicles, roads, traffic lights, power grids, greenhouses, and the surrounding environment, the number of connected devices has the potential to reach over 20 Billion devices by 2020 [3].

The predicted proliferation of IoT devices and networks has begun to emerge on a very large scale, thereby giving rise to the proliferation of sensor applications across multiple application domains, and in turn, to the generation of a huge volume of data [3]. These data, however, reside in unconnected silos, across vertical application domains. There is, thus, an increasing interoperability gap across the multiple unconnected silos of sensor data, hampering the emergence of a truly connected world between people, things and processes. In a bid to solve the exacerbating IoT interoperability challenge, due to the increasingly heterogeneous elements of the IoT [4], various approaches have been proposed for addressing IoT interoperability across multiple domains [5]–[8]. However, the IoT interoperability challenge has remained, and continues to hinder the emergence of the true IoT paradigm.

In this paper, we present our preliminary work on a novel, hybrid approach to the IoT interoperability challenge, which spans the various levels of IoT interoperability to address the challenge in a holistic and integrated manner. Our approach combines previous approaches for addressing technical and semantic interoperability, while leveraging on the Sensor Markup Language (SenML) standard, to address syntactic interoperability.

II. RELATED WORK

Holistic IoT interoperability holds the key to unlocking the IoT potential in the coming years. Thus, any attempt to effectively address the challenge of limited interoperability, requires a clear understanding of the ramifications of IoT interoperability. In their report [9], Serrano et. al. described IoT interoperability across four levels, namely; the technical, syntactic, semantic and organizational interoperability levels. Addressing interoperability at each of these levels requires different approaches. So far, four major approaches have been identified in the literature, including standards [6], gateway [7], middleware [10] and semantic web [11] approaches. Gazis, [6], in his survey of standards for M2M and IoT, argued that the standardization of the key IoT interoperability areas, which he highlighted as services, communication, data and support, held the key to effectively addressing the IoT interoperability challenge. These key interoperability areas, according to him, map in some manner to the various levels of interoperability. His work further identified the gaps for future standardization efforts, which included developing standards for information and semantics, edge-computing and near-data processing, security and privacy, as well as the reliance on machine intelligence for deductive reasoning and information assimilation, from the myriad of application scenarios for IoT. Aloi et. al. [7] proposed a smartphone-centric multi-technology gateway to enable IoT interoperability. They argued that majority of IoT devices communicate using either BLE, WiFi, ANT+ or ZigBee communication technologies. As such, they implemented a prototype of their gateway, using

978-1-5386-4980-0/19/$31.00 ©2019 IEEE

smartphones, pre-equipped from the manufacturer with BLE, WiFi and NFC radios, and which they further equipped with a micro SD ZigBee card. Razzaqque et. al. [12] presented a very comprehensive survey on IoT middleware. In their survey, they highlighted the key architectural, functional and non-functional requirements for IoT middleware, while also providing a grouping of existing and proposed middleware solutions, based on their design approaches. These design approaches included service-oriented approaches and event-based approaches, among others. They also identified challenges associated with existing middleware solutions, highlighting the fact that, in addressing the architectural requirements of middleware solutions, majority of the existing solutions did not provide support for syntactic and semantic interoperability. Similarly, Gyrard et. al. [8] addressed data and semantic interoperability for IoT applications, using the semantic web approach. From fundamental IoT concepts, they introduced linked data principles for the web into the IoT paradigm, for acquiring data about sensors, the sensed data and the sensing environment, thereby creating a Web of Things (WoT). They further applied a robust ontology framework to create semantically meaningful representations and understanding of WoT data, thus, providing reasoning over IoT data, and extracting inference in a semantically meaningful way. They also developed a semantic engine to enable developers create semantic web of things (SWoT) applications. Their work also provided a detailed review on existing semantic web approaches to addressing IoT interoperability.

However, each of these approaches addressed one or two IoT interoperability levels, and that, in isolation, thereby leaving IoT devices and networks largely unconnected and in turn, making IoT data inaccessible across multiple application domains. There is, therefore, a need for a holistic and integrated approach to addressing the IoT interoperability challenge.

III. TOWARDS A UNIFIED COGNITIVE IoT GATEWAY FRAMEWORK

A. A Holistic Look at IoT Interoperability

Despite the amount of research that has gone into addressing the IoT interoperability puzzle, the IoT community is yet to arrive at a holisitc interoperability solution for the complex IoT ecosystem. The inadequacy of previous attempts at fully addressing IoT interoperability, is based on the failure to address IoT interoperability from the ground up, beginning with technical interoperability. Therefore, we argue that a scalable and robust approach to addressing IoT interoperability must consider technical, syntactic and semantic interoperability, thereby, allowing for a holistic approach to addressing IoT interoperability. While IoT gateway approaches have sought to address technical interoperability (from hardware (devices and networks) and software (messaging protocol/application layer) perspectives [7]), standardization approaches [6] have sought to establish some specific set of standards for IoT, to allow for interoperability. Conversely, semantic web approaches to IoT interoperability [8] have focused majorly on semantic interoperability of the IoT, while totally ignoring technical interoperability and sparsely addressing syntactic interoperability. Middleware approaches [10] on the other hand do not provide for a holistic way to address technical, syntactic and semantic interoperability in an integrated manner.

Meanwhile, the authors of [13] proposed the concept of dynamic (adaptive) interoperability. They argued that dynamic interoperability techniques and methodologies were needed to achieve the needed lasting solution to IoT interoperability challenges within the current, complex IoT landscape. This implies that IoT devices should be able to enter and interoperate within the IoT ecosystem without the need for heavy modification, a characteristic responsible for the explosion and ubiquity of the current internet. Thus, in the light of the foregoing, none of individual approaches to IoT interoperability (IoT gateways, middleware solutions, semantic web approaches, ND standardization) are sufficient by themselves to achieve the needed interoperability for IoT. Thus, we argue that any effort that would represent a holistic IoT interoperability solution must firstly find a way to align the four approaches to IoT interoperability, such that a middleware-enabled gateway is implemented, within the framework of specific IoT standards, that allows for the implementation of semantic web based solutions. This implies a hybrid approach to addressing IoT interoperability. We also argue that a hybrid approach that would scale must have elements of adaptability and cognition, to allow for seamless integration between devices, networks and application users..

B. IoT Gateway as a Cognitive Dynamic System

One of the earliest mentions of cognition in conjunction with the IoT paradigm was in the work of Wu et. al. [14]. They argued that infusing the current IoT with cognitive capabilities was necessary for addressing the myriad challenges of IoT and realizing its true potential. They further argued that it was necessary to empower IoT with high-level intelligence. Haykin & Fuster [15] also provided a discourse on cognition. The authors described the idea of a cognitive dynamic system from an engineering and neuroscience perspective, inspired by the human brain and based on earlier novel and seminal works on cognitive radios and cognitive radar respectively. Their work, which described cognitive dynamic systems as a new way of thinking, vocalized the silent dialog between neuroscientists and scientists focused on the dynamics of information networks in complex adaptive systems. They further posited that cognitive dynamic systems can be modeled after the cognitive functionality of the brain. These functions include; the perception-action (P-A) cycle, multi-layer memory, attention and intelligence, are necessary functions that a system must perform to attain cognition. Each of these functions, as a continuum, build on the previous function in a layered manner, such that the end goal of the cognitive dynamic system is to be able to intelligently adapt itself in its interaction with its environment [16]. Thus, relating the above discourse to the interoperability challenge of IoT, and leveraging the concept of Cognitive Dynamic Systems in [15] we argue that cognitive intelligence, at the topmost level of cognitive functionality, is needed to entrench a holistic approach to IoT interoperability, given the heterogeneity of devices, networks, protocols, services and application needs, as well as the diverse domains of IoT. For this, we must establish a framework for incorporating perception, memory and attention into the architecture for IoT, to achieve the needed intelligence for interoperable IoT.

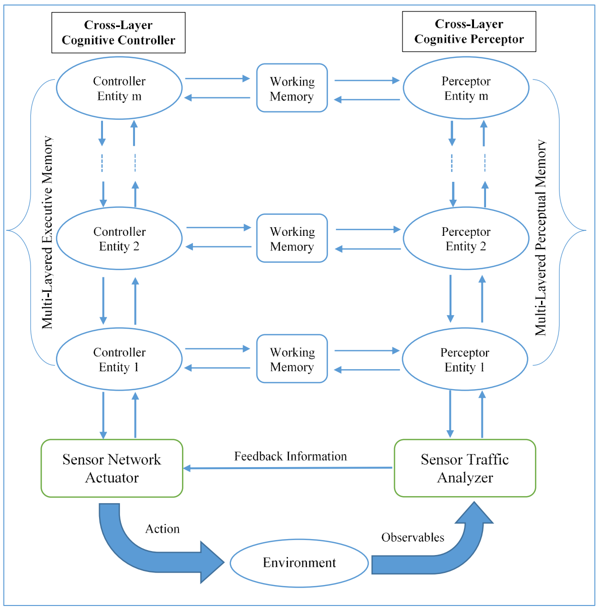

Fig. 1: Functional Block Diagram of the Cognitive IoT gateway as a Cognitive Dynamic System.

To put the above within the context of IoT, heterogeneous devices and sensors, equipped with heterogeneous communication technologies, exist within the IoT ecosystem, which are used to gather a variety of environment observables. These observables range from product identification tags (RFID) to weather information (weather sensors) to the state of roads, buildings or energy meters, as may be applicable to smart transportation, smart buildings or smart energy, for the purpose of argument. For IoT to be cognitive, it is incumbent on an IoT infrastructure, say a gateway, to be able to firstly decipher what kind of sensor/tag data requires transmission. Just as the practical use of cognitive radio is motivated by the desire to address the electromagnetic spectrum underutilization problem [16], cognitive IoT seeks to deliver technical, syntactic and semantic interoperability in an integrated manner, to the IoT interoperability problem. Thus, to accomplish this, the interface of the cognitive perceptor required to perform such an assessment could be a sensor traffic analyzer, whose purpose is to decipher what category of sensor data is available for transmission. The feature of interest in the incoming data is stored in the perceptual memory, and a feedback is directed to the cognitive controller, which may set up a new signal reception radio stack for the cognitive perceptor and may also request for transmission parameters to be sent by the sensor data transmitter. It is also possible that the gateway has acquired previous knowledge about data transmission parameters for the newly emerging IoT data (stored as a cognit – a unit of knowledge representation in cognitive dynamic systems [15]). Such knowledge may be combined with new features of interest in the data, namely the sensor data, and stored in the perceptual memory. Also, the stored information can be used to activate a new perceptor entity within the cross-layer cognitive perceptor, while requesting the environment to confirm transmission parameters through a network information advertisement broadcast. It is evident from the above description that perceptual attention, which is the efficient allocation of resources has been activated, without the gateway having to suffer from an information overload problem. At the same time, the cognitive controller has made a decision that translates to cognitive intelligence for the IoT gateway. Fig. 1 shows the functional block diagram of the cognitive IoT gateway, as a cognitive dynamic system. The entire CIoT gateway (IoT cognitive dynamic system) perpetuates a global P-A cycle between the sensor traffic analyzer, the sensor network actuator and the environment, while within the various layers of the cognitive IoT architecture that derives from the cognitive IoT gateway, an internally composite P-A cycle is embodied. This is represented by the feedback loop between the multi-layered perceptual memory, instantiated as perceptor entities, and the multi-layered executive memory, instantiated as controller entities, and reciprocally coupled through the working memory. While we do not attempt to mathematically model the cognitive IoT system as a whole, we formalize a key process that starts up the cognitive intelligence cycle within the framework of the gateway, and that address technical interoperability for IoT in (C) below. This process is the multi-protocol parsing for addressing software-biased technical (messaging protocol) interoperability, as a proof of our concept of cognitive IoT. Syntactic interoperability can be addressed by leveraging a standardized data format, for example, the Sensor Markup Language (SenML), while semantic interoperability can be abstracted as an RDF data clustering problem. The foregoing will be addressed in future research reports.

C. A Formal Approach to Technical Interoperability

The current IoT landscape features multiple communication protocols. These protocols span multiple communication layers. We adopt the 4-layer IoT protocol stack of [17] for communication between IoT devices and the cognitive IoT gateway. Thus, we have protocols across the link, network, transport and application layers. While link layer protocols are hardware-biased, dependent on radios that manage PHY/MAC communication, network, transport and application layer protocols are software-biased. Common link layer protocols include IEEE 802.15.1, 802.15.4, 802.11x, LoRAWAN, and LTE-NB among others. So far, we abstract the identification of link layer protocols within the Sensor Traffic Analyzer of the gateway. This may be treated as a cognitive radio problem but is beyond the scope of this paper and as such is not addressed. We initially choose to adopt a standards approach to network layer communication. Thus, for a simple case, we assume a single-protocol (IETF IPv6 Routing Protocol over Low-power, Lossy Networks) network layer. We also assume that either of Transmission Control

Protocol or User Datagram Protocol is used for transmission at the transport layer. For the transport layer, an open source protocol parsing library (Libtrace [18]) can be used. Therefore, at the application layer, we considered an interoperability scenario where incoming sensor data carries any of three application protocol headers, including; CoAP, MQTT and AMQP. The choice of these three protocols is based on the fact that, a larger percentage of current IoT infrastructure implements one of these protocols at the application layer. Thus, in the light of the IoT gateway as cognitive dynamic system, that is able to sense incoming sensor data and acquire same successfully, there is a need for a multi-protocol translator or a multi-protocol parser, for addressing technical interoperability. We, thus, address the multiple messaging protocols challenge with a multi-protocol parser.

Within the current internet infrastructure, protocol parsers have been used in firewalls and intrusion prevention systems. A lot of such parsers have been implemented with finite automata (for binary protocols) and in some other cases, context free grammars. Since our test case scenario features multiple binary protocols (CoAP, MQTT and AMQP), the abstraction of a Deterministic Finite Automaton is adequate for addressing our multi-protocol parser. Our choice of the DFA as an appropriate abstraction for protocol parsing is motivated by the work of [19]. The authors, commenting on the performance of FA-based parsers, posit that such parsers are sufficiently expressive for meaningful protocols, sufficiently performant for high-throughput applications, and sufficiently simple to construct and maintain. The parser implemented in this work is a hand-coded, selective and precise parser. The authors in [20], on commenting on FA-based, hand-coded, selective and precise protocol parsing, agreed that the strategies employed by this class of parsers are appropriate for protocol identification.

The first eight bits of the protocol headers for CoAP, MQTT and AMQP can be shown to uniquely identify any data packet carrying any of the protocol headers. Thus, based on these bits, we constructed a regular expression, P, for the multi-protocol parser, given by:

$$P = (01\,(0{+}1)\,(0{+}1)\,(01\,(0{+}1)\,(0{+}1)\,{+}1000)) \cup 00010000 \cup 01000001. \quad (1)$$

The regular language for the regular expression in (1) is given by:

$$L(P) = \{0(0010000 + 1(0 + 1)\,(0 + 1)\,(1000 + 0(001 + 1(0 + 1)\,(0 + 1))))\}. \quad (2)$$

The language in (2) can uniquely identify and parse incoming sensor data at the application layer with CoAP, MQTT or AMQP headers. Thus, based on (2), we constructed a DFA (see Fig. 2) that identifies and parses CoAP, MQTT and AMQP based sensor data. This DFA, thus, becomes the multi-protocol parser for multiple messaging protocols in the cognitive IoT gateway. The DFA is easily implementable in C or Java. Details of the multi-protocol parser and its implementation for a cognitive IoT gateway s reported in another paper. Also, future research would explore machine learning approaches to multi-protocol parsers.

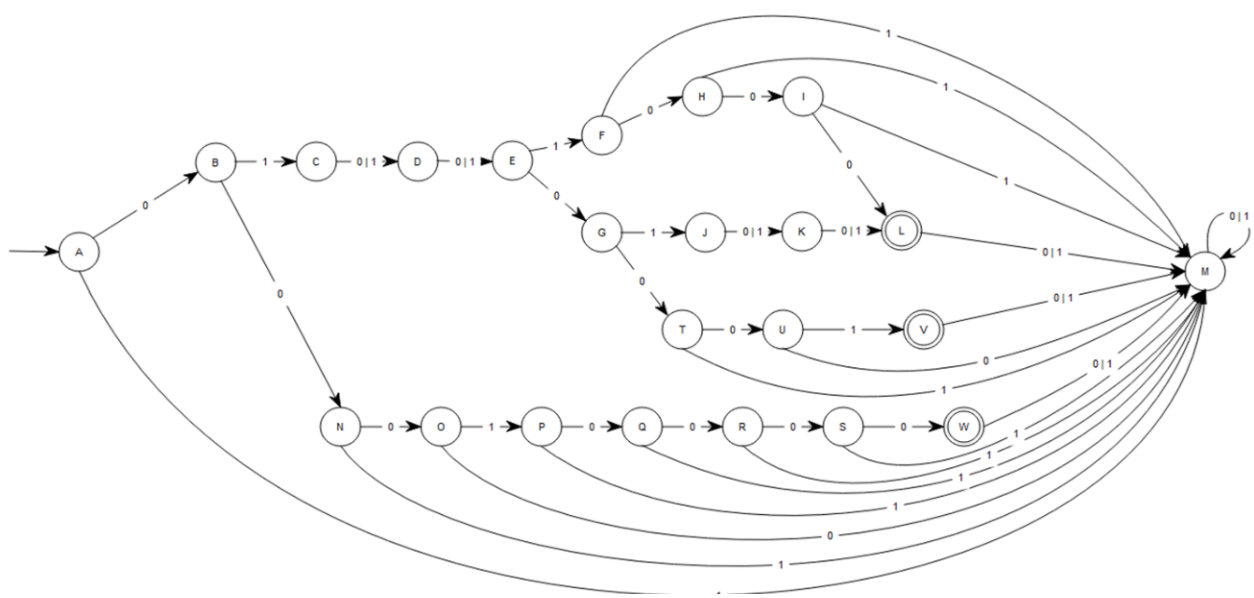

Fig. 2: DFA to recognize language, L(P) for AMQP, CoAP and MQT

IV. THE COGNITIVE IoT GATEWAY FRAMEWORK

We present our developed cognitive IoT gateway framework in this section. The gateway framework (Fig. 3) favors a fog-based, distributed approach for implementing an IoT gateway. Each gateway is equipped with an adaptive radio for connecting with IoT devices and a software defined implementation of a LTE UE. This makes individual gateways addressable at a global level with their unique IP addresses within a given LTE network. The gateway further registers every new device that communicates with it and stores its information in its devices database. The ID of each device is sent, along with the annotated data from such device, to any IoT cloud platform, so that each device is addressable from the IoT cloud platform/domain application. The gateway is also addressable from the IoT cloud platform/domain application. This ensures that every device is transparently addressable from the application layer of the IoT. The gateway senses incoming sensor data to ascertain what communication protocols to instantiate, sets up required communication protocol stack for reliable reception of transmitted sensor data, registers each IoT device connecting to it newly and allocates an ID to the device within its devices registry, accepts all incoming sensor data traffic based on defined rules in its Adaptive Middleware Layer runtime engine, parses all accepted sensor data through its multi-protocol parser, annotates all parsed sensor data with semantic metadata based on the application domain of sensor data, interprets and transfers all command functions to IoT devices from the cloud/user application, performs computation and analytics on data from a sensor/group of sensors based on the rules set in the AML runtime engine, manages raw/computed/analyzed data stored in its data store through its Information Visualization and Management Module, provides a distributed file service in conjunction with other gateways within a region (LTE network), and implements end-to-end data, network and device privacy and security.

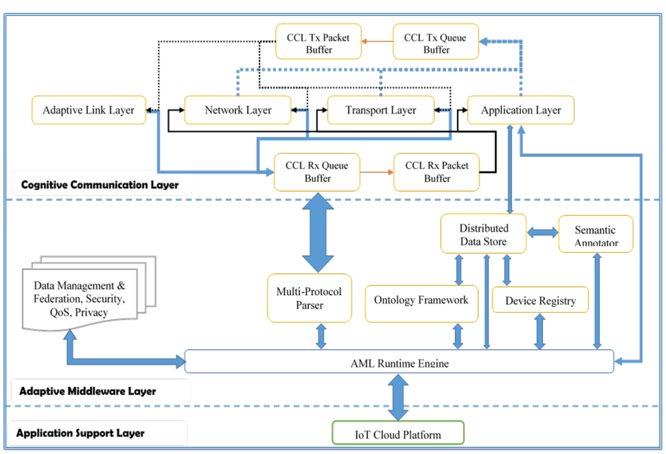

Fig. 3: Cognitive IoT Gateway Framework

A performance analysis of the developed cognitive IoT gateway framework is necessary to ascertain the viability of the approach for IoT gateways. Preliminary performance has been carried out using Real Time Calculus based Modular Performance Analysis. This analysis will be reported in future papers.

V. CONCLUSION

This paper discussed preliminary work in the development of a cognitive IoT gateway framework for addressing IoT interoperability from a holistic perspective, covering the technical, syntactic and semantic interoperability levels of IoT. The paper also explored the formalization of the multi-protocol technical interoperability problem for IoT as a DFA problem, that sought to design a finite automaton, which recognizes a language that combines multiple IoT application layer protocol headers. A DFA was therefore, designed, which understands the language of three application protocols, including the CoAP, AMQP and MQTT. While this is by no means an exhaustive list of protocols, the formalism seeks to present the current solution as a proof of concept that the technical interoperability problem of the IoT can be completely formalized and modeled with appropriate mathematical abstractions, thereby making the problem tractable and solvable in polynomial time. While this paper opens up the discourse of cognitive IoT from a new perspective, beginning with the discussion of a cognitive IoT gateway as a cognitive dynamic system, there are still questions to be addressed. These questions include:

1. Does the cognitive gateway fit into the formalism of the general cognitive dynamic system? If it does not, what approach should be used in developing a formal model for the gateway as a cognitive dynamic system? There is therefore a need to further think about what appropriate formalism would effectively represent the cognitive IoT gateway as a cognitive dynamic system.
2. What is the best abstraction for the sensor traffic analyzer in the cognitive IoT gateway that makes it accessible to all classes of capillary networks from near field communication and RFID networks to short, medium and long range standards based and proprietary networks like ZigBee and LoRAWAN, among others?
3. What other approaches can be used to address protocol parsing and semantic interoperability at the gateway level, given the computational constraints of the gateway?

These questions ensue from the preliminary work described in this paper, opening up the opportunity to further innovate in the area of cognitive IoT for addressing the interoperability challenges of the IoT enterprise. Furthermore, the concept of cognition needs to be addressed rigorously for identity management, privacy and security within the context of the IoT, as this has not been addressed yet.

REFERENCES

[1] A. A. Al-sabbagh, R. A. S. Alsabah, and A. Y. Mjhool, “An extensive review : Internet of things is speeding up the necessity for 5G,” *Int. J. Eng. Res. Appl.*, vol. 5, no. 7, pp. 106–112, 2015.

[2] A. Biral, M. Centenaro, A. Zanella, L. Vangelista, and M. Zorzi, “The challenges of M2M massive access in wireless cellular networks,” *Digit. Commun. Networks*, vol. 1, no. 1, pp. 1–19, 2015.

[3] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, “Internet of Things (IoT): A vision, architectural elements, and future directions,” *Futur. Gener. Comput. Syst.*, vol. 29, no. 7, pp. 1645–1660, 2013.

[4] A. Al-Fuqaha, M. Guizani, M. Mohammed, A. Mohammed, Ayyash, and Moussa, “Internet of Things: A Survey on Enabling Technologies, Protocols and Applications,” *IEEE Commun. Surv. Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.

[5] P. Grace, J. Barbosa, B. Pickering, and M. Surridge, “Taming the interoperability challenges of complex IoT systems,” in *Proceedings of the 1st ACM Workshop on Middleware for Context-Aware Applications in the IoT - M4IOT ’14*, 2014, pp. 1–6.

[6] V. Gazis, “A Survey of Standards for Machine-to-Machine and the Internet of Things,” *IEEE Communications Surveys and Tutorials*, vol. 19, no. 1. pp. 482–511, 2017.

[7] G. Aloi *et al.*, “A mobile multi-technology gateway to enable IoT interoperability,” in *Proceedings - 2016 IEEE 1st International Conference on Internet-of-Things Design and Implementation, IoTDI 2016*, 2016, no. I4t, pp. 259–264.

[8] A. Gyrard, M. Serrano, and P. Patel, “Building Interoperable and Cross-Domain Semantic Web of Things Applications,” in *Managing the Web of Things: Linking the Real World to the Web*, no. December, 2017, pp. 305–324.

[9] M. Serrano, P. Barnaghi, F. Carrez, P. Cousin, O. Vermesan, and P. Friess, “Internet of Things - IoT Semantic Interoperability: research challeges, best practices, recommendations and next steps,” 2015.

[10] S. Soursos, I. P. Zarko, P. Zwickl, I. Gojmerac, G. Bianchi, and G. Carrozzo, “Towards the cross-domain interoperability of IoT platforms,” in *Proceedings of the 2016 European Conference on Networks and Communications.*, 2016, pp. 398–402.

[11] A. Gyrard, P. Patel, S. K. Datta, and M. Intizar, “Semantic Web meets Internet of Things (IoT) and Web of Things (WoT),” in *Proceedings of the International Semantic Web Conference*, 2016, pp. 1–10.

[12] M. A. Razzaque, M. Milojevic-jevric, A. Palade, and S. Clarke, “Middleware for Internet of Things : A Survey,” *IEEE Internet Things J.*, vol. 3, no. 1, pp. 70–95, 2016.

[13] O. Vermesan (Ed), *Advancing IoT Platforms Interoperability*: River Publishers. 2018. Accessed on: November. 2, 2018. [Online]. doi: 10.13052/rp-9788770220057

[14] Q. Wu *et al.*, “Cognitive Internet of Things: A New Paradigm Beyond Connection,” *IEEE Internet Things J.*, vol. 1, no. 2, pp. 129–143, Apr. 2014.

[15] S. Haykin and J. M. Fuster, “On cognitive dynamic systems: Cognitive neuroscience and engineering learning from each other,” *Proc. IEEE*, vol. 102, no. 4, pp. 608–628, 2014.

[16] S. Haykin, “Cognitive dynamic systems: Radar, control, and radio [point of view],” *Proc. IEEE*, vol. 100, no. 7, pp. 2095–2103, 2012.

[17] R. Sutaria and R. Govindachari, “Making sense of interoperability: Protocols and Standardization initiatives in IOT,” in *2nd International Workshop on Computing and Networking for Internet of Things (CoMNet-IoT) held in conjunction with 14th International Conference on Distributed Computing and Networking (ICDCN 2013)*, 2013, pp. 2–5.

[18] S. Alcock, P. Lorier, and R. Nelson, “Libtrace: A packet capture and analysis library,” *Comput. Commun. Rev.*, vol. 42, no. 2, pp. 43–48, 2012.

[19] R. D. Graham and P. C. Johnson, “Finite state machine parsing for internet protocols: Faster than you think,” *Proc. - IEEE Symp. Secur. Priv.*, vol. 2014–Janua, pp. 185–190, 2014.

[20] A. X. Liu, C. R. Meiners, E. Norige, and E. Torng, “High-speed application protocol parsing and extraction for deep flow inspection,” *IEEE J. Sel. Areas Commun.*, vol. 32, no. 10, pp. 1864–1880, 2014.