Towards Cloud Integration for Industrial Wireless Sensor Network Systems

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Abstract- **The paper discusses the advantages and challenges for a cloud-based system architecture for process monitoring and statistical analysis of network performance. The focus is on integrating industrial wireless sensor networks (IWSN), composed of low-power wireless field devices for sensing and actuation, with cloud infrastructures, enabling remote access over secure real-time communication channels. The proposed cloud integration solution implements RESTful services at a coordinator node level of the WSN, allowing the implementation of a scalable and more performant communication infrastructure. The overall system allows functionality for visualization, data storage and processing and distributed algorithms that can run across heterogeneous multi-level monitoring and control systems. We present a modeling and simulation approach for scalable IPv6-based industrial wireless sensor networks, highlight effective mechanisms for cloud interoperability and argument the feasibility of the proposed system.**

Keywords: cloud infrastructures, service-oriented architecture, industrial wireless sensor networks, process monitoring and control, IPv6, routing.

I. INTRODUCTION

Implementing monitoring and control applications based on Industrial Wireless Sensor Networks (IWSN) has been proven to bring great benefits in specific application domains where there is a need for information gathering over a dynamically distributed area [1]. Dynamic deployment of sensor nodes, their automatic discovery, self-organization and distributed data gathering mechanisms make IWSN architectures highly flexible and scalable according to application needs at a specific moment of time. The main drawbacks of IWSNs are the limited capacity of the network nodes and the low level interrogation for accessing network data.

Cloud computing brings great advantages when it comes to extending the capabilities of a system by using virtualized resources that allow access to increased storage, increased processing power and software execution platforms. With the emergence of IoT (Industry of Things) technologies, integrating WSN into the cloud comes as a natural direction for further development. The main challenges that need to be addressed in a WSN-cloud architecture consist of the abstraction at the application level that allows the engineer to focus more on how to implement the desired functionality and less on the WSN configuration and low level programming. Service Oriented Architecture (SOA) systems provide an Internet-based approach where application level – field level interaction is translated into a more flexible communication.

Concerning cloud integration of wireless sensing and actuation systems deployed for process monitoring and control applications, this can be implemented for industrial wireless sensor networks (IWSN) [1] in two ways. One of the more established alternative in the field of IWSN, the embedded sensing and actuation network is isolated in the plant facility at the process level. A central coordinator manages the nodes and handles every interaction with the outside world. All external requests are handled by the coordinator and the incoming data stream from the nodes is parsed at this level [2]. A prominent example of IWSN architecture implementation is supported by the WirelessHART standard [3]. The main goal is to integrate legacy wired HART protocol devices and new wireless low-power intelligent field devices in a common network. WirelessHART implements low-power wireless communication in the unlicensed 2.4 GHz ISM band and offers robustness and redundancy by deterministic access to the radio channel by means of TDMA and multi-path routing [4]. This imposes stringent network-wide time synchronization mechanisms, coordinated by the central node, in order to compensate for clock drift and to assure efficient allocation of the assigned slots [5]. By leveraging IPv6 protocols such as 6LoWPAN, the nodes can be individually accessed and managed across the cloud. Depending on the local available resources, the need for a border router can arise, with the role of compressing packet headers and addresses. However, this solution poses considerable security challenges as individual nodes have to be protected from attackers from outside and within the node (malicious nodes). Cloud integration is therefore approached at the gateway/coordinator level which, given specific access rights, decides which data can be relayed towards the field devices.

This paper presents a framework for the integration of IWSN in a cloud environment. The purpose of this framework is to provide a solution for mapping the low level

IWSN access solutions to with higher levels abstraction mechanisms, enabling the easy coupling for remote monitoring, data storage and WSN performance analysis applications. RESTful web services are provided for an easier integration of IWSN data into high level business management applications like ERP (Enterprise Resource Planning) or MES (Manufacturing Execution Systems).

The remainder of this paper is structured as follows. Section II introduces the main concepts behind IWSN, SOA and cloud architectures and summarizes the related work in this area. Section III presents the proposed system architecture. Section IV gives the service implementation and cloud integration details of the proposed framework. Section V presents the simulation results of IWSN behavior based on the proposed architecture. The final section concludes this works and highlights directions of future research.

II. Background and Related Work

Several papers addressed some of the main challenges that arise in the effort of increasing accessibility to IWSN data for monitoring and control applications. The main research directions arise from IWSN inter-node communication and connection to the cloud level, addressing different SOA approaches that provide high level of abstractization for WSN keeping in mind the and in the end addressing aspects regarding cloud integration.

A. IWSN

A starting point and method for introducing the specific challenges and constraints faced by wireless sensor networks operating in industrial environments as opposed to non-critical applications like environmental monitoring. A classification is also carried out depending of the nature of the process task: monitoring, control [6] and safety. IWSNs have been successfully used at the first level, while ongoing research work is carried out to reliably implement control loops over such systems. Safety-critical systems still overwhelmingly rely on wired, redundant system architectures for compliance [7]. The WirelessHART standard is widely viewed as one of the implementation solutions, having the best outlook for adoption and integration in industrial automation systems. IPv6 systems are emerging as an interesting alternative and offer particular advantages in order to improve the scalability and management of the overall distributed monitoring and control system based on embedded low-power devices.

B. WSN – SOA approaches

SOA represents a set of architectural principles that encapsulate functions into generic services which are transmitted over a communication network.

One of the first studies that addressed the issue of defining a web service architecture for WSN was presented in [8]. This study extends the common DPWS (Devices Profile for Web Services) stack for standard web services communication by a WSN-SOA stack that allows the web service structure implementation on low capacity nodes. In [9] a middleware solution for a node communication gateway and service generation is provided. The authors design a service-oriented API that allows access to WSN data using a gateway that uses SQL queries for inter-module communication and data storage. The structure makes the data, as well as network information and events management, available as web services. A field level approach is presented in [10], where the web services are deployed directly on the WSN nodes, allowing their easy integration in an enterprise or engineering application. As the authors point out, this solution shows great results in transmitting large amount of data at a time, over larger periods, because of the performance overhead needed for message communication.

C. Cloud mechanisms and IWSN integration

Cloud platforms are mainly designed to provide high-level data center capabilities by allowing user access to increased storage and processing power and a large number of hardware and software resources. This solves some important performance limitations of IWSN, but may increase the bandwidth load. The cloud interaction focuses on two directions: user-cloud interaction and cloud data interaction.

Cloud structure models come with three basic types of services: Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). SaaS is a software delivery method that provides user specific services managed by the cloud provider. PaaS provides a development environment similar to an operating system that allows the user to run its applications on the cloud platform. IaaS provides the greatest flexibility as it delivers access to cloud storage and processing resources, allowing the user to deploy its own software applications.

Most research studies focus on defining the architecture for WSN – cloud integration [11] - [14]. In [11] a basic model for a SaaS cloud for WSN data analysis is provided. In [12] the authors present a solution for extending the applicability to critical systems. Paper [13] focuses on facilitating the data transfer between the WSN and the cloud platform, providing details regarding the implementation, message format and inter-module communication. A model for separating the function layers in cloud architecture, allowing the seamless integration of WSN expert and programmer responsibilities is proposed in [14].

The salient application domains for cloud – IWSN implementation are in precision agriculture, distributed environmental monitoring, intrusion detection, highly distributed processes, etc. The dynamic structure and distributed architecture of cloud platforms make them not suitable for the requirements of process control applications. In [13] a series of WSN application scenarios are presented, including rainforest rehabilitation and water quality monitoring.

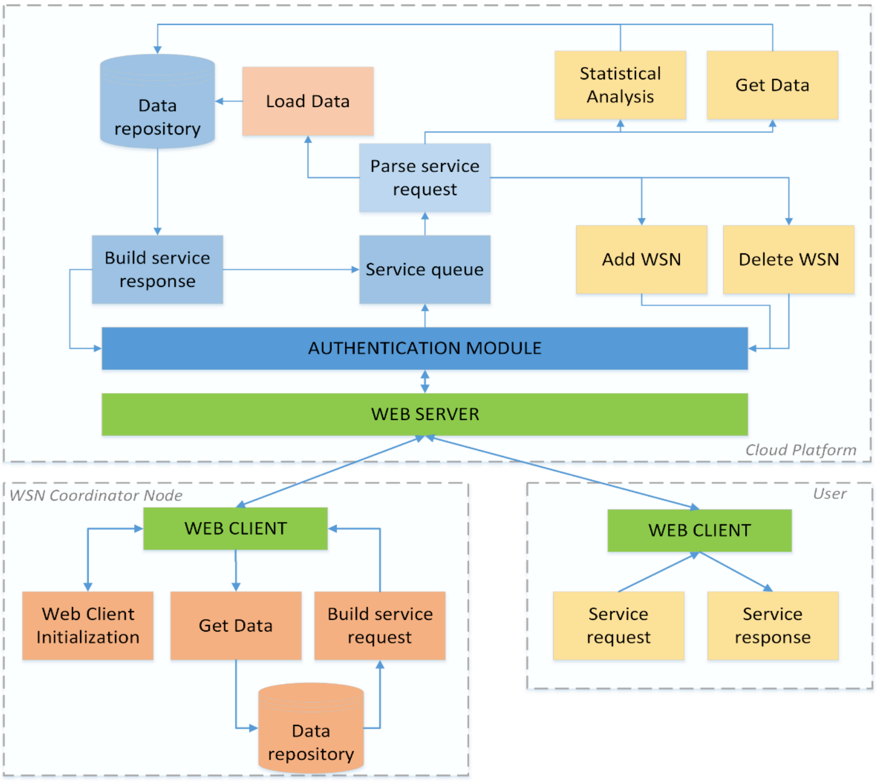

Fig. 1. Inter-module communication for IWSN integration in a Cloud Platform

III. System Architecture: Design and Implementation

Integrating IWSN in a cloud environment must adapt the available solutions and define application-specific interrogation and message structures. Our solution considers IWSN architectures where the low-power field devices connect to a central coordinator node responsible for network management and data gathering. Inter-node communication uses the 6LoWPAN protocol that enables individual addressing of network nodes. The WSN can be connected to the cloud using one more several sinking points, thus providing support for redundant configurations.

The proposed system components and their interaction were presented in Fig. 1. It considers using RESTful services both for making the WSN data available in the cloud and also for user-cloud interaction. REST (Representational State Transfer) is a modern software architecture, designed for scalable web services implementation. RESTful services are web Application Programming Interfaces (APIs) which adhere to REST architectural constraints and represent an increased performance and easier scalable alternative to the more common SOAP technology. Even more, the SOAP dependability of the XML data format makes it inapplicable for highly constrained sensor nodes [10]. By providing and enforcing an uniform interface, REST, which includes the identification of resources through URIs (Uniform Resource Identifier) in web systems, becomes highly suitable to networks of thousands of ubiquitous intelligent embedded devices. Even if they are considered less secure, by encapsulating them over the TCP/IP protocol, RESTful services are enabled with the error detection and automatic packet retransmission capabilities. This makes them suitable for non-critical data acquisition applications. The presented concept considers that the data transmission is continuous and cyclic once a connection between the coordinator node and the cloud was established.

This structure implements can be implemented for example over a SaaS cloud provider.

A. *WSN coordinator node*

To enable the coordinator to be able to interrogate a cloud platform, the coordinator must implement a web client application that will allow the interaction with the web server from the cloud platform. The communication will require the WSN coordinator authentication using the Kerberos method presented in [13]. The authentication procedure will allow the cloud to correctly identify the WSN and to transmit, along with the connection accept response, the time period at which the data will be transmitted. After this initialization procedure, the WSN coordinator starts retrieving sensor data from the data storage repository and building a StoreData service request for the cloud platform.

B. *User services*

To be able to access cloud services, a user will have authenticate using his unique credentials. For the user, four types of services are available:

- *AddWSN*: this type of service allows a user to define the identification parameters of the coordinator node in a WSN network. Also, the data structure and the cycling period on which the WSN coordinator sends the data is defined by the user in this request. The cycling period will be set at the WSN coordinator node at its web server initialisation request. Several coordinator nodes working in a redundant configuration can be defined. Only predefined coordinator nodes can connect to the cloud infrastructure.
- *DeleteWSN:* requesting this service will delete all information related to the specific WSN ID, including its stored data and processing analysis results.
- *StatisticalAnalysis:* this service will provide the user analysis of statistical WSN infrastructure regarding available nodes, maximum, minimum and average node load etc.
- *GetData:* facilitates the user with access to the required data.

All services are available in correspondence with a user-WSN allocation table.

IV. SIMULATION RESULTS

In order to showcase our approach, we have carried out modeling and simulation work for a reference WSN architecture based on IPv6 RPL-UDP networking and competitive concurrent radio channel access in the form of the carrier-sense multiple access (CSMA) with clear channel assessment (CCA) mechanism implemented in ContikiMAC. The Contiki/COOJA environment for deploying networks of resource constrained devices, was used for implementation. This offers increased flexibility in configuring the WSN, as well as detailed simulation at the network and node levels, extending up to instruction level through emulation of the specific hardware architecture. Also, in enables quick evaluation with the cloud architecture previously defined by collecting data at the WSN coordinator node and disseminating it throughout the cloud.

A 20 node WSN was defined based on the TelosB/Sky mote embedded architecture, which includes a MSP430 microcontroller paired with a CC2420 low-power 2.4GHz radio transceiver. The simulated nodes are randomly deployed in the field with node 1 acting as the network sink while nodes 2-20 are tasked at periodically reporting data towards the sink. The sink initially sends out broadcast messages and waits for answers from the neighboring nodes, during the network set-up phase. Nodes which are not in the sink's range, first identify their own neighbors and subsequently the best routes toward the sink are identified and periodically classified. Fig. 2 illustrates the sensor map topology with overlayed information regarding the ETX indicator for link evaluation. Black dots represent the individual nodes while the blue lines and associated values represent the link score associated to each vertex of the network graph

The radio propagation model selected for defining the simulation environment is the Unit Disk Graph Medium (UDGM) with distance loss model, in which a node can only communicate with a peer which is found in a circular area of diameter *d*. This simplifying assumption does not account for more complex radio communication propagation issues such as reflections, multi-path or for asymmetric link which can occur in real world conditions. It compensates however by reduced complexity, allowing the designer to focus on the networking and data processing architectures, or, as is the case with our deployment for gateway-level cloud infrastructure integration.

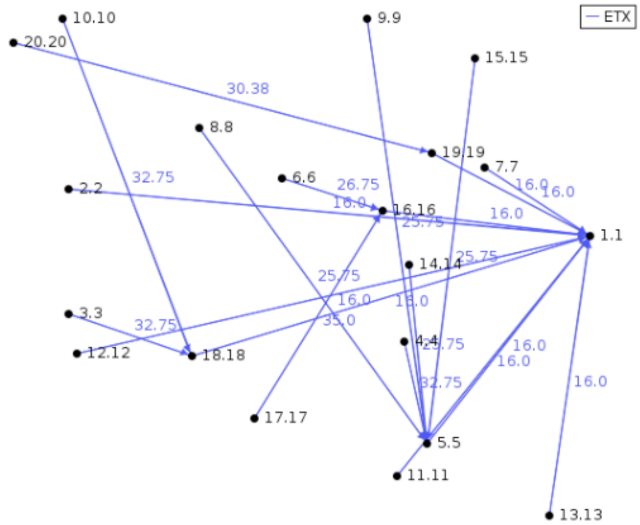

Fig. 2. Simulated wireless sensor network map.

The simulation is run for 20 minutes (simulated time with a 150% speeding factor in relation to actual time), during which all relevant data from the network is collected and stored. This includes all node activity, network logs and individual and aggregated statistics for the radio communication and networking layers. It allows in-depth post-simulation analysis of node and network performance and subsequent tuning of key parameters.

One example of aggregated statistics is the average routing metric presented in Fig. 3. It can be seen how this indicator has a steady decrease from a value around 850 in the beginning towards 450 around the end of the experiments. This can be explained by the fact that the self-organization procedure at the network level takes some time before establishing the best routes from the end-nodes to the sink. In the absence of significant interference, affecting some or all of the links, the indicator should stabilize around a steady-state value. As this represents an aggregated indicator, the routing metrics at the packet and node level should be also considered for more in-depth analysis of the network behavior and decision.

At the higher data level, a prioritization scheme can be introduced in order to speed up the transmission of critical information or control commands over the wireless sensor network, based on the aggregated network statistics. The interfaces toward the web based service architecture into the cloud has to support a multi-level priority system for such implementations.

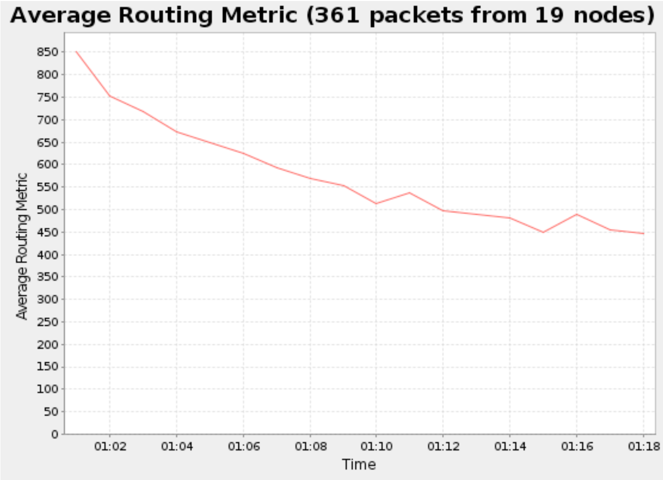

Fig. 3. Average routing metric across the experiment.

Fig. 4 presents the historical power consumption across the experiment for the 20 nodes. As in the case of the previous analyzed indicator, the power consumption is higher in the network set-up phase [8], reflecting increased communication and processing activity for neighbor discovery and route set-up. Subsequently the values decrease, but with occasional spikes, especially in the case of critical router nodes which have the dual task of transmitting their own messages and relaying those of neighboring nodes towards the sink. This information can be used to provide energy-balancing routing algorithms that are able to guarantee quasi-fair depletion of the node's energy resources.

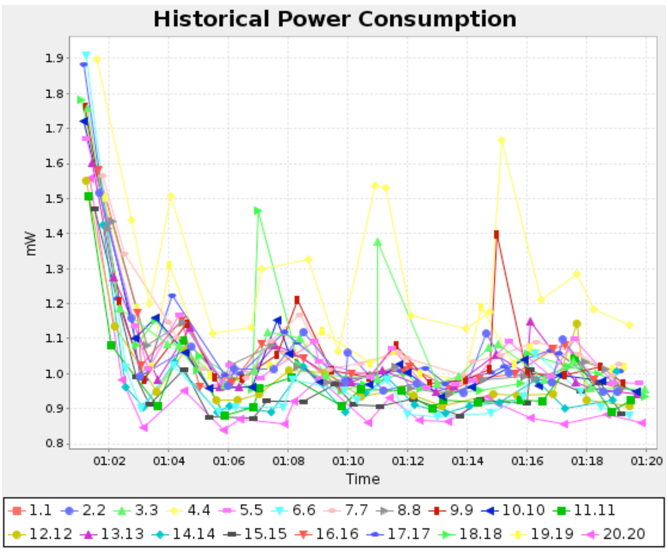

Fig. 4. Overall power consumption of the nodes.

Aggregated network statistics are collected at the WSN coordinator node and forwarded towards the cloud for analysis and storage. Table I shows some of the information that can be extracted by the cloud infrastructure, regarding network status. These include: the average number of hops, routing metric and ETX indicator.

TABLE I
AGGREGATED WSN STATISTICS

Indicator	Value
Number of hops	1.26
Routing metric	567.97
ETX	18.23

Subsequently, the network data collection topology can be extended and improved. We present one method to implement this by adding a second data sink to the network. Fig. 5 presents the layout with node 21 acting as the second sink. This provides improved failure robustness and redundancy for both the local system and the cloud system. Sink 21 is represented in the overall architecture as an additional WSN coordinator node, by replicating all the pre-defined properties and methods of node 1. Some issues with this approach concern network congestion, as it is illustrated in the case of node 13 which now reports and communicates to both sinks.

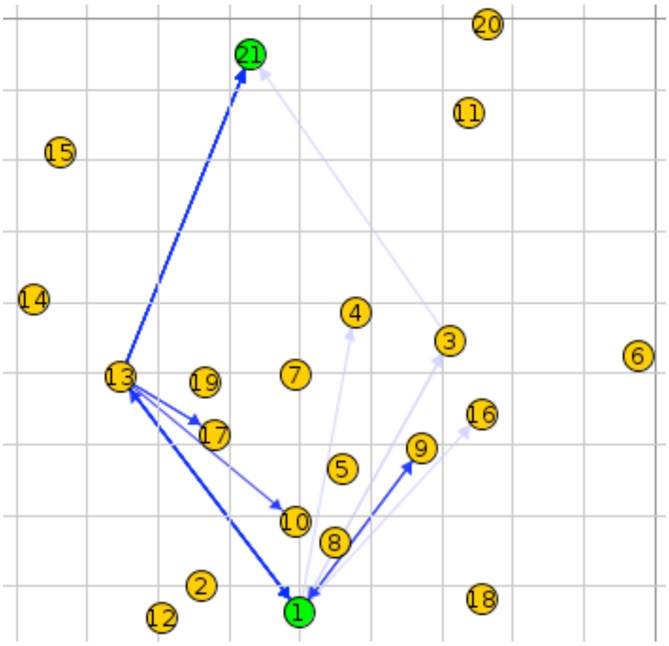

Fig. 5. Enhanced dual-sink network topology.

V. CONCLUSIONS AND FUTURE WORK

This paper presented and architecture that supports the integration of IWSN into a cloud computing platform. The proposed solution is adapted to the limited resources of WSN node, enabling data storage and network management analysis. The paper proposes a solution for web service implementation structure and details the inter-module communication.

We use a simulation approach to reflect network operation at the field level and the integration with the higher level cloud infrastructure. By applying suitable tools, efficient insight can be gained, allowing for the optimization of the overall system. The WSN coordinator node is seen as the key item for enabling the integration of these large scale monitoring systems into reliable and resilient clouds for data acquisition, processing and storage. Future work is targeted at a pilot implementation on physical sensor nodes and designing and deploying suitable software interfaces for protocol conversion and data alignment.

ACKNOWLEDGMENT

This work was partially funded by the National Research Programme PNII, project 257/2014: Cloud Architecture for an open Library of Complex re-Usable Logical function blocks for Optimized Systems – CALCULOS. Grigore Stamatescu's work was has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398

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