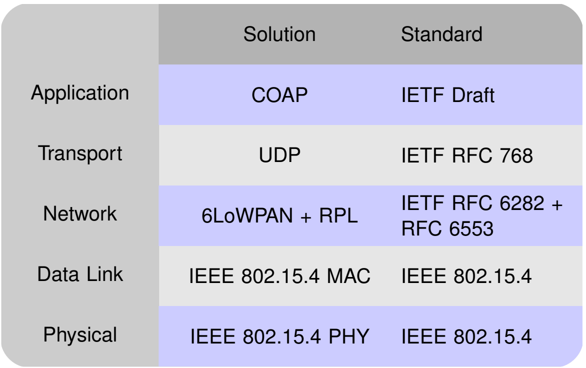
Implementing the Internet of Things Vision in Industrial Wireless Sensor Networks

C.P. Kruger *† and G.P. Hancke †‡
*Advanced Sensor Networks Research Group, Counsil for Scientific and Industrial Research, South Africa.
†Department of Electrical, Electronic and Computer Engineering, University of Pretoria, South Africa.
‡Department of Computer Science, City University of Hong Kong, China.
Email: ckruger1@csir.co.za and ghancke@ieee.org

***Abstract*—The authors of this paper explore the use of IPv6 over Low power Wireless Personal Area Networks (6LoWPAN), IPv6 Routing Protocol for Low power and Lossy Networks (RPL) and Constrained Application Protocol (CoAP) as a possible solution for realising the Internet of Things (IOT) vision in Industrial Wireless Sensor Networks (IWSNs). The aim of this paper is to investigate the feasibility of using Internet Engineering Task Force (IETF) standards in industrial environments by identifying and quantifying several attributes of a 6LoWPAN, RPL and CoAP based IWSNs relating to bounded time interval communications. The paper identifies several possible causes of latency in IWSNs and can be used as a basis for deploying Internet Protocol (IP) based IWSNs requiring IOT connectivity.**

***Index Terms*—Wireless Sensor Networks (WSN); Internet of Things (IOT); Latency; 6LoWPAN; CoAP; RPL.**



	Solution	Standard
Application	COAP	IETF Draft
Transport	UDP	IETF RFC 768
Network	6LoWPAN + RPL	IETF RFC 6282 + RFC 6553
Data Link	IEEE 802.15.4 MAC	IEEE 802.15.4
Physical	IEEE 802.15.4 PHY	IEEE 802.15.4

Fig. 1: IP based IWSN stack and associated standards.

I. Introduction

The Internet of Things (IOT) is a term commonly used to identify a system consisting of uniquely identifiable objects, autonomous in nature and able to connect to the Internet to present and exchange real-world information in a digital form. The Internet of Things will consist of many smart objects, created by augmenting every day objects with sensing, processing and networking abilities. The main attribute of an industrial communications network is the ability to reliably communicate in a bounded time interval [1] and is thus a key requirement for introducing smart objects into industrial environments.

The use of networked control systems (NCSs) [2] over low-power and lossy networks (LLNs) for industrial environments as discussed in [3], [4] and [5] present several advantages over wired systems [1], [6]. These advantages include extended network coverage, cost effective installations, self organising network topologies, resilience against single node failure and straight forward configurations. The Internet of Things vision contains may parallels to NCSs based on IWSNs, motivating the use of Wireless Sensor Network (WSN) technology to implement industrial smart objects.

The Internet Protocol (IP) for Smart Object communications alliance (IPSO) vision was identified as a standards based solution for implementing smart objects in industrial environments. The technology was selected due to its interoperability possibilities with existing IPv6 infrastructure [7], allowing seamless integration of networked infrastructure with constrained wireless devices as initially proposed by [8]. The aim of this paper is to investigate the feasibility of using 6LoWPAN in combination with the RPL routing protocol for industrial wireless sensor networks (IWSNs). This task will require investigation into several attributes of the protocol, each task relating to the protocol‘s ability to communicate over LLNs while maintaining reliable, time-bounded communications. The investigation is however limited to the network, transport and application layers in Fig. 1 where most of the Internet Engineering Task Force (IETF) standardisation for IOT applications is being implemented.

This paper is organised as follows: Section 2 introduces a standards based design for a 6LoWPAN, RPL and CoAP based IWSN. The section discusses several design requirements and attributes for IWSNs and how the existing technology relates to the use of 6LoWPAN, RPL and CoAP for industrial applications. Section 3 presents and discusses results obtained from several experiments that were conducted to investigate the real-time performance of the TinyOS BLIP 2.0 6LoWPAN stack. Section 4 forms a conclusion on using 6LoWPAN and RPL based IWSNs for implementing the Internet of Things vision in industrial environments.

II. 6LoWPAN and RPL for industrial applications

An IOT network topology for a smart factory is presented in Fig. 2 and consists of a wired plant automation network connected to an IWSN. The plant automation network is

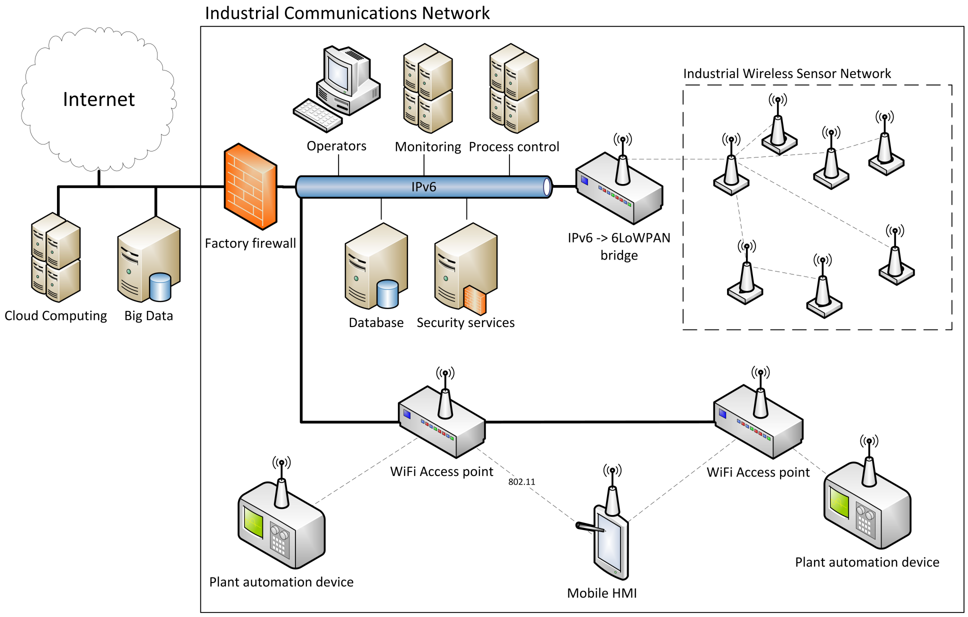


Fig. 2: Industrial communications network design.

ideally directly connected to the internet; requiring a firewall to protect the network form unauthorised access. Internet connectivity is used to integrate with existing Big Data and Cloud Computing infrastructure. The plant automation network is implemented on standard 802.3 Ethernet networking equipment and the assumption is made that the Ethernet or Fiber-optic based network has ample bandwidth, low jitter and fast response times when compared to the IWSN. The plant network additionally uses 802.11 Wi-Fi connectivity to enable remote access to existing plant automation devices and mobile human machine interfaces (HMIs).

Standardisation and interoperability is a key aspect of industrial communications as explained in [1]. Non standardised IWSN implementations have the freedom to innovate, but are plagued by interoperability at architecture level [9]. A key requirement for implementing the IOT vision in IWSNs is thus a network design that makes use of IPSO standards [10]. The IPSO stack is based on open standards and are thus well suited for NCS consisting of multi-vendor equipment. The use of standards simplifies the NCS design process and allows sensing and actuation devices from different vendors to be interconnected. A recent paper [11] shows how 6LoWPAN and RPL implementations from TinyOS and ContikiOS were used together in the same network, even though the two implementation were developed independently of each other. Particularly important fact is that IP for smart objects do not just apply to 6LoWPAN networks over the 802.15.4 standard, but also to various physical layer technologies including Low Power Wi-Fi, Bluetooth Low Energy (BLE) and G3 PLC.

The stack used in this paper is summarised using the OSI layered approach depicted in Fig. 1 and will focus on mesh networking using RPL on top of the IEEE 802.15.4 physical (PHY) and medium access control (MAC) layer specifications for implementing the IWSN.

III. An experimental IP based IWSN deployment

The aim of the experimental IP based IWSN deployment is to quantify the latency in the IETF standards stack in order to asses if the selected IOT stack will be suitable for industrial application where predictable latency and reliable communications is a key requirement. Experiments were conducted in TinyOS using the BLIP 2.0 6LoWPAN stack and consisted of TelosB sensor network nodes that were used to simulate a linear, star and mesh network topology. The effect of hop count, gateway delay and variable packet sizes on round trip time (RTT) was tested in the experiments.

A. Linear topology experiments

The latency experiment was conducted to examine the effect of varying the distance associated with the communication paths. The experiment made use of two sensor network nodes as depicted in Fig. 3. The RTT was measured between nodes A and B, incrementing the distance by one meter on each measurement. Twenty RTT measurements were made using the ping6 command and an average was obtained for each increment in distance. The experiment was conducted up to a distance of 30 meters. The experiment was conducted twice, once at a CC2420 transmission power setting of 31 dBi (max) and again at 5 dBi (min).

The results from the measurements are shown in Fig. 4 and Fig. 5. An initial average latency of 30 ms was measured and varied as the distance increased and transmission power reduced. The graph shows a constant RTT up to 10 m after which the RTT times vary. Fig. 5 shows how the RTTs of individual measurements remains fairly constant at a distance of 1 m and varied significantly at the final distance of 30 m.

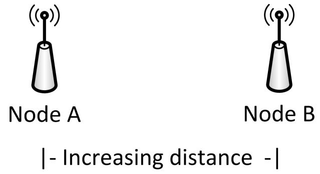


Fig. 3: The experimental setup that was used for the latency experiment.

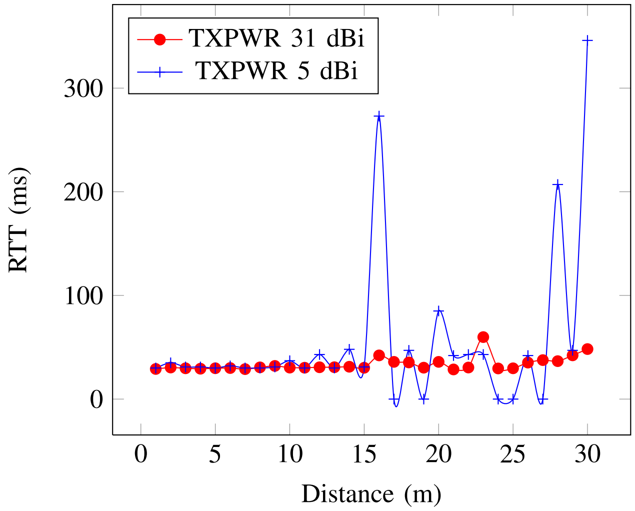


Fig. 4: The RTTs that were obtained from the latency experiment.

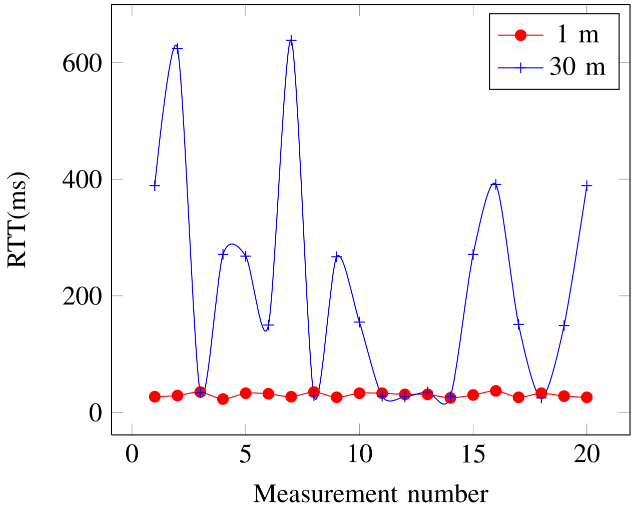


Fig. 5: The non-averaged RTTs that were obtained from the latency experiment.

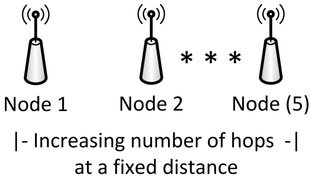


Fig. 6: Illustration of the multi-hop experiment.

The multi-hop experiment consisted of five nodes that were placed in a linear configuration as shown in Fig. 6. The distance between the nodes was fixed at 6 m intervals and the transmission power of each node was reduced so that only adjacent nodes were within communication range. The RTTs from the first node to each of the additional hops in the network was measured. The gateway delay experiment was conducted to determine how much additional delay the 6LoWPAN to IPv6 conversion process adds to the overall latency of data travelling into and out of the IWSN. The experimental setup is depicted in Fig. 7. RTTs were obtained by measuring the time a packet takes to travel from a personal computer (PC) on an IPv6 network to a specific node on the 6LoWPAN section of the system. Nodes on the 6LoWPAN network were arranged in a linear pattern that is identical to the multi-hop experiment. The results of the gateway delay and multi-hop experiment is shown in Fig. 8.

B. Star topology experiment

A star topology experiment was conducted to asses the possible addition of latency due to adjacent sensor network nodes, continuously accessing a central point. The experimental setup is depicted in Fig. 9 and consisted of four TelosB motes spaced 4 m apart. All motes communicated directly with the centrally located root node.

An automated bash script was used to facilitate the data collection process, executing ping6 commands with variable ICMP packet sizes to collect minimum, average, maximum and deviation statistics for RTT analysis. Results obtained from executing the ping6 command from the root node as well as PC to each node in the network is shown in Fig. 10. Fig. 11 graphs the latency vs packets size for the four nodes measured from the PC through the root node, simulating a gateway device using variable packet sizes. The individual average, minimum and maximum RTT data collected through the root node using a 56 byte ICMP packet is shown in Fig. 12.

C. Mesh topology experiment

A mesh topology organised in a grid like structure was used to investigate the effect that variable packet sizes and hop-count would have on the various RTTs inside the network. The routing topology obtained; by allowing RPL to form the network is shown in Fig. 13. A bash script was used to automate the data collection process, allowing the execution of various ping commands with variable ICMP packet sizes. The script would cycle through all the nodes in the mesh network collecting minimum, average, maximum and deviation statistics.

The average RTT time and maximum deviations for all the nodes in the mesh network is shown Fig. 14. Node one experienced high RTTs due to frequent routing topology changes between nodes 1, 2 and 5. The effect of the topology changes are also evident in Fig. 15 where node one experienced significant packet loss when compared to other nodes in the

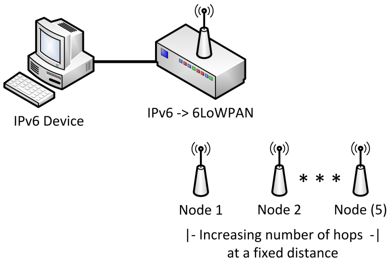


Fig. 7: Gateway delay experiment.

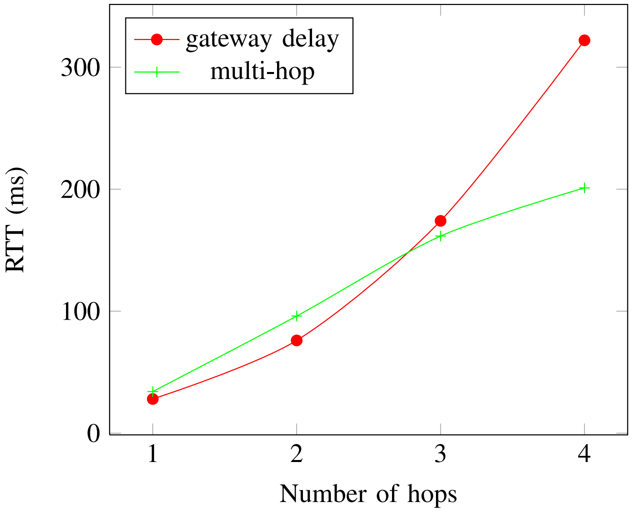


Fig. 8: RTTs vs number of hops obtained for the gateway delay and multi-hop experiments.

network. In contrast node four experienced very little packet loss even though it was four hops away from the root node.

IV. Discussion

The results obtained form the linear latency experiments showed that the delay introduced by the communications channel is negligible for short distances, and the delay on the sensor network node is by far the predominant factor when no RF obstacles or interference exist. The experiments showed that the distance between nodes only became relevant when signal strength decreases. Weak signals and interference resulted in zero to minimal packet loss, but triggered excessive retransmissions that severely effected RTTs in the network.

Latency and reliability experiments conducted in [12] using the previous version of the TinyOS BLIP stack found that the RTT increases due to a combination of maximum packet size in the fragmentation process and ICMP payload size. The use of the previous version of the BLIP stack unfortunately limits the comparable results, but does confirm the zero to minimal packet loss and excessive retransmission results obtained in the linear latency experiment.

Experiments conducted in [13] were conducted using FreeRTOS and the NanoStack 6LoWPAN stack developed by Sensinode Inc. The experiments measured the packet delivery ratio and latency between a client computer, through a gateway device to a specific node in the 6LoWPAN network, comparable to the gateway delay experiment in this paper. The Sensinode stack achieved an average latency of 64 ms for one hop and 90 ms for two hops in contrast to the 28 ms and 76 ms obtained in this paper. The authors of this paper used a 54 byte ICMP header in contrast to the 4, 8, 16 and 37 byte headers in [13]. The testbed layout in [13] used a grid like structure 3 m apart in contrast to the linear, star and mesh topologies that were examined by this paper.

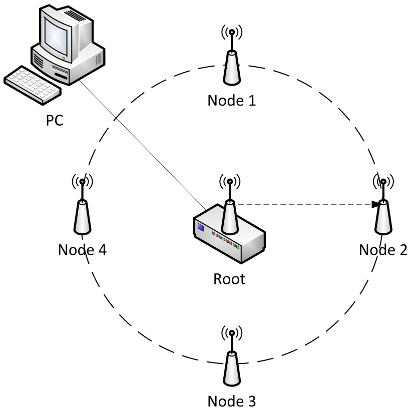


Fig. 9: The star topology experiment.

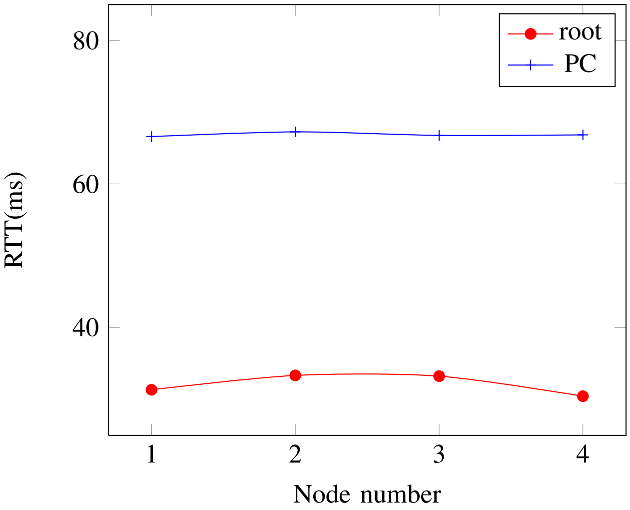


Fig. 10: Latency to each node for the star topology experiment.

The multi-hop experiment indicated that the RTTs increased in a linear manner at least up to the 3rd measurement as shown in Fig. 8. The non-linear behaviour of the 4th hop can be explained as an environmental anomaly caused by varying RF conditions as explained by [14] and re-emphasises the effect of channel characteristics on latency. The development of optimal routing protocols based on the number of hops [15] or channel conditions are thus beneficial.

The star topology test obtained an average latency of 66 ms to the nodes inside the star network when a gateway device was present. The results are comparable to the 65 ms obtained

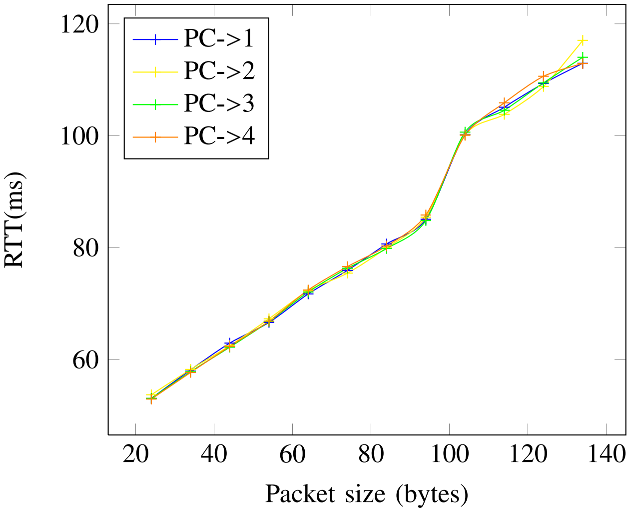


Fig. 11: Latency vs packet size for the star topology experiment with the gateway delay included.

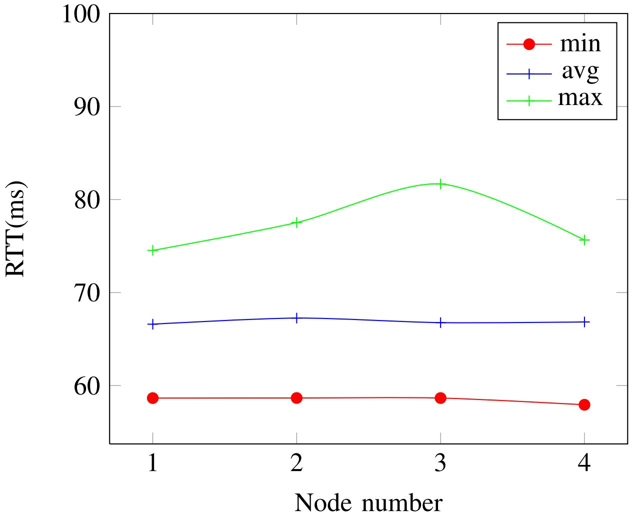


Fig. 12: Latency deviations to each node in the star topology experiment.

in [13], as well as with the delays obtained in the linear and gateway delay experiments for gateway and non-gateway measurements.

The mesh topology experiment was used to investigate the effect that variable packet sizes and hop-count would have on the various RTTs inside a mesh topology. Increased RTTs were observed in a more dense network topology, similar to [13] confirming that dense mesh networks experience higher RTTs than sparse networks.

The routing topology obtained in Fig. 13 was similar to the results in [16] where ContikiOS was used as the sensor network operating system. The obtained topology was not very efficient, initially routing data away from the end destination, increasing latency unnecessarily. Frequent routing topology changes were also observed which had an undesirable connectivity loss affect in the network.

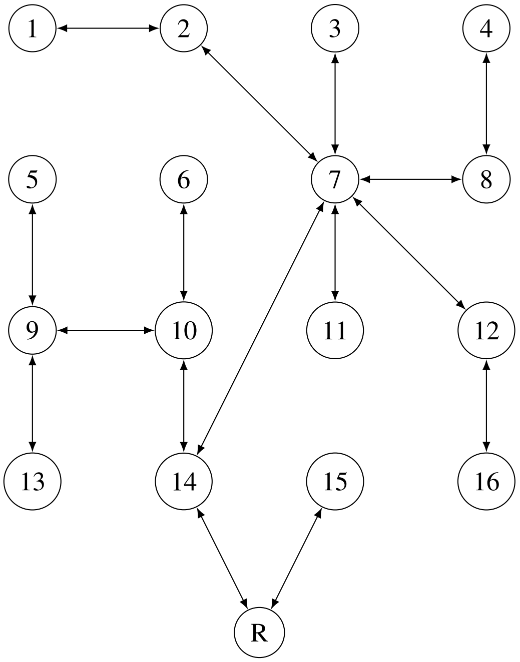


Fig. 13: The RPL routing topology obtained in the mesh experiment.

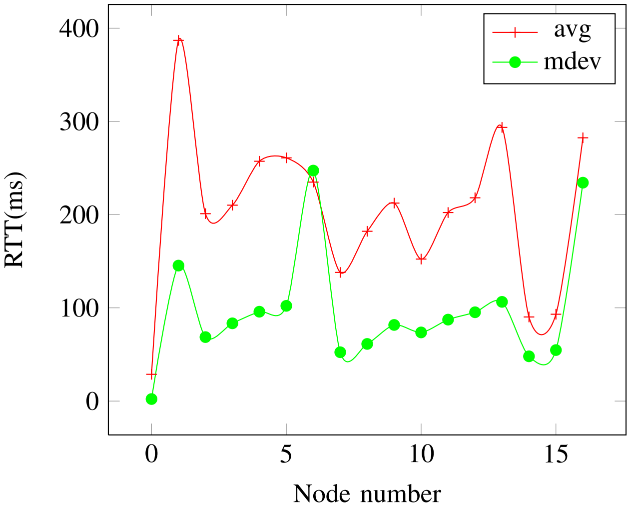


Fig. 14: Average RTT time and maximum deviations for a 56 byte ICMP packet travelling in the mesh network.

It is important to conclude the discussion by stating that a WirelessHEART IWSN implementation [17] obtained an average latency of 2000 ms during deployment testing. The relatively high latency is due to the TDMA methods and superframe scheduling used in the deployment, but does raise the question whether or not beacon enabled 802.15.4 based systems are suitable for IOT applications where low latency is a key requirement for RESTful communications.

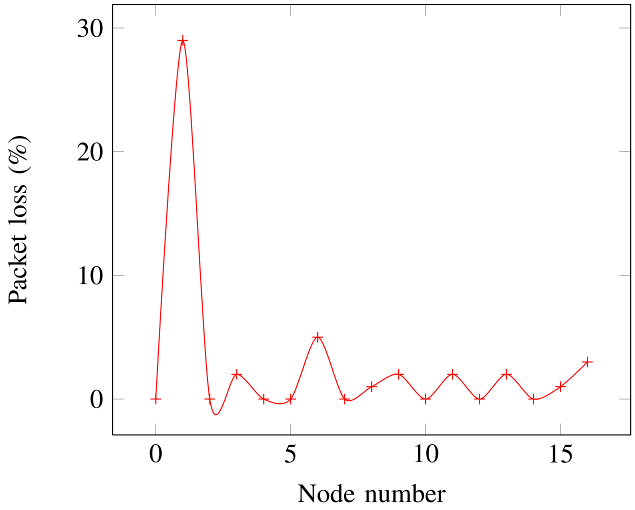


Fig. 15: Packet loss obtained in the grid RTT experiment.

V. CONCLUSIONS AND FUTURE WORK

The concept of using IETF standards to implement the Internet of Things vision in an IWSNs based NCS was investigated. The authors focused on bounded time interval communications and conducted latency, multi-hop and gateway delay experiments in mixed topologies to better understand the various parameters that may influence IP based IWSN design. The results showed that IP based IWSNs implemented using the current TinyOS Blip 2.0 IP and TinyRPL stack exhibit a hop count limitation and that processing activities relating to the sensor network nodes were responsible for the majority of the round-trip delay. Latency in an IP based IWSN can be affected by multiple factors as listed below.

- Varying characteristics of the communications channel
- Unsynchronised radio transmissions
- Frequent retransmission of lost packets
- Excessive data fragmentation and reassembly
- Frequent changes in routing topology

A 6LoWPAN and RPL based IWSN was found to be suitable for industrial applications where the factors that influence latency are strictly controlled through proper network design and deployment. IWSNs based on LLNs are however not suitable for mission critical applications and should be restricted to low priority control processes that can tolerate the latency quantified in this paper. The results obtained in this paper emphasises the importance of correctly deploying sensor network nodes using the following guidelines.

- A site survey is required to determine a suitable channels where the IWSN can operate free from interference.
- When deploying IWSN devices one should be mindful of the RF parameters that affect transmission and reception performance.
- The number of hops to the gateway device should be reduced as much as possible to reduce latency.
- Small packet sizes assist in reducing latency and should be considered when writing IWSN applications.

Proper spectrum analysis and network debugging tools are thus essential in the deployment and continuous operation of an IWSN. The analysis of 6LoWPAN and RPL for industrial applications showed that many opportunities exist to improve the existing factors that influence latency and that the TinyOS Blip 2.0 IP stack is a practical technology for extending the Internet of Things vision into industrial environments.

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