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Evaluation of an RPL/6LoWPAN/IEEE 802.15.4g Solution for Smart Metering in an Industrial Environment

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***Abstract*—This paper describes the evaluation of a multi-hop wireless networking solution for Smart Grid metering in an industrial environment. The solution relies on RPL, 6LoWPAN, and IEEE 802.15.4g protocols, and has been implemented using low-power and low-capacity devices. Also, it supports both TCP and UDP protocols to transport traffic from DLMS/COSEM Smart Grid metering applications. The experimental tests took place in an industrial environment during 20 days. The obtained results allowed the characterization and evaluation of the developed solution and can be used as a basis to evaluate other 6LoWPAN/IEEE 802.15.4g networking solutions.**

I. INTRODUCTION

The IEEE standard for Smart Utility Network, IEEE 802.15.4g [1], along with the IPv6 protocol suite, which includes 6LoWPAN and RPL, are aiming at being a key enabler of the Internet of Things. Smart Grids are one of the main areas where IEEE 802.15.4g/IPv6 networking solutions are expected to penetrate more rapidly. Some examples of Smart Grid applications are the Advanced Metering Infrastructure, Distribution Automation, and municipal street lighting.

Our main contribution is the experimental evaluation in an industrial facility of a multi-hop wireless networking solution that we developed for Smart Grid applications using low-power and low-capacity devices. The developed networking solution is based on the IEEE 802.15.4g/IPv6 protocol suite and relies on a passive link quality monitoring mechanism. For our tests we have selected a radio configuration with low transmission power and low data rates in order to stress the overall solution. To the best of our knowledge, this is the first experimental evaluation of an RPL/6LoWPAN/IEEE 802.15.4g solution for Smart Metering in an industrial environment. Due to space constraints, we present a brief description of the developed solution and the main experimental results. More details can be found in [2].

The paper is organized as follows. Section 2 describes the developed solution. Section 3 describes the experimental setup. Section 4 presents and discusses the experimental results. Finally, section 5 draws the conclusions and presents the future work.

II. DEVELOPED SOLUTION

The multi-hop networking solution is implemented by joining the IEEE 802.15.4g layer 2 protocol with the IETF Low-Power and Lossy-Networks (LLNs) protocol suite, which includes 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) [3] [4] and RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [5]. Fig. 1 shows the protocol stack of the developed solution. All nodes have a single IEEE 802.15.4g network interface. There are two type of nodes, the Local Border Router (LBR) and the Local Router (LR). On the left, the LBR is simultaneously an RPL DAG (Directed Acyclic Graph) root and the default gateway for all the LRs in its network. The LR may act both as router, by forwarding IP packets, or host, by terminating UDP or TCP sessions. In the deployed solution, each LR is connected to a Smart Meter (SM) (on the right), but an LR may be deployed alone (on the center), for coverage extension purposes; in this case, the LR only does IP forwarding, and does not process the protocols above IPv6/6LoWPAN.

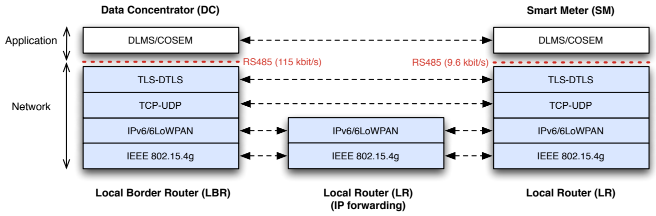

Fig. 1. Protocol Stack associated to three types of equipment: 1) on the left, the Local Border Router (LBR) is the networking module of the Data Concentrator (DC), which implements the DLMS/COSEM client; 2) on the center, an equipment for coverage extension purposes, composed by the Local Router (LR), only performing IP forwarding; 3) on the right, the LR is the networking module of the Smart Meter (SM), which implements the DLMS/COSEM server.

The overall solution was developed with DLMS/COSEM Smart Grid metering applications in mind. It follows the DLMS/COSEM TCP/IP communication profile [6]. The LBR and LR interface with the DLMS/COSEM equipments through RS-485 UARTs with 115 kbit/s and 9.6 kbit/s data-rates, respectively. The LBR interfaces with a Data Concentrator (DC) – a DLMS/COSEM client, typically at the Power Transformer

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(PT) –, while the LR interfaces with a SM – a DLMS/COSEM server.

The LBR platform has an ARM926 operating at 400 MHz with 16 Mbytes of SDRAM, while the LR has a Cortex-M4 operating at 120 MHz with 160 kbytes of SRAM. The transceiver is the Atmel RF215, compliant with the standards IEEE 802.15.4-2011 and IEEE 802.15.4g-2012. It operates at sub-GHz and 2.4 GHz frequency bands, has a maximum transmission power of 14 dBm, and sensitivity down to -123 dBm. We used standard 2 dBi omnidirectional antennas for the 900 MHz band. The operating system is the FreeRTOS and the IPv6 stack is based on the Lightweight TCP/IP stack (LwIP).

The RPL implementation uses the non-storing mode to reduce the processing and memory resources used in LRs. For our experimental tests we used Objective Function (OF1), which gives the path with lowest cost as a function of both hop count and link quality. Since the RF215 transceiver did not provide Link Quality Indicator and we wanted to get an estimation of the link quality without the overhead of active link quality monitoring, we used a four samples simple moving average of the Energy Detection. In order to minimize traffic overhead and increase resiliency, LRs use IPv6 Stateless Auto Configuration; the default gateway is the RPL DAG root, whose IPv6 address is delivered in the RPL DIO messages.

III. EXPERIMENTAL SETUP

The testbed deployed to evaluate the developed networking solution in a real environment is shown in Fig. 2. It depicts the facility aerial photo, the positions of the equipments, and the typical network topology. The equipments are two PTs (PT1 and PT7) and the 10 SMs. Each PT has a DC/LBR set installed. In order to stress out the networking solution we disabled the DC/LBR at PT1 (bottom) forcing all SM/LR to connect to the DC/LBR at PT7 (left). The building on the left is a canteen, in the centre is an office building. The main part of the right building is a warehouse with some offices at the North side. For reference, we present the typical network topology to help understand the network behavior. For the sake of clarity, to reduce the number of variables evaluated, security at both layers 4 and 2 was disabled. Therefore, DLMS was transported directly over TCP or UDP, and there was no overhead from security protocols. The transceivers were configured to operate in channel 7 of the 915 MHz band with a bandwidth of 2 MHz, O-QPSK as the modulation scheme, and a 250 kbit/s data rate. The transmission power was set to 14 dBm and the RF215 sensitivity for this modulation scheme was -102 dBm.

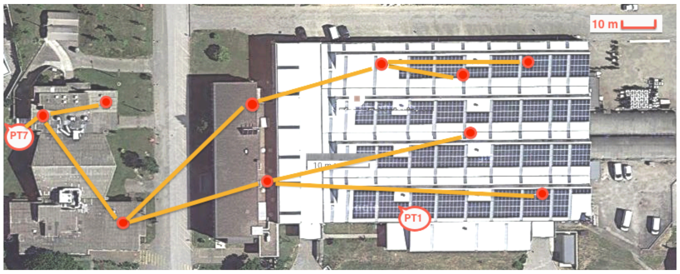

Fig. 2. Facility, position of the equipments, and typical network topology.

The performance tests were made in three stages. Firstly, the *ping* tool from a PC attached to the LBR through an Ethernet port was used to measure the hop distance between the SM/LRs and the DC/LBR, and the round-trip time (RTT) and packet loss ratio (Two-Way) at the IP layer over a 11.5 days period. The test consisted of continuous rounds of pings to all the LRs. 100 consecutive ping requests with 4 seconds interval were made to each LR in each round. A total of 2510 sets of 100 ping requests were made. Secondly, the DLMS/COSEM application was used to measure the performance of the DLMS protocol over TCP and UDP during 7 days. DLMS session duration and failure ratio, were measured. 20,000 DLMS rounds were made. The transport was switched between TCP and UDP every 30 minutes. Each DLMS round consisted of 3 consecutive DLMS sessions to each SM/LR. The timeout and maximum number of DLMS retransmissions was set differently depending on the transport protocol used. A timeout of 5 seconds and a maximum of 8 retransmissions were configured for UDP, while for TCP a timeout of 60 seconds and 1 retransmission were used. The DLMS request and response messages have a length of 64 bytes and 128 bytes, respectively. The DLMS session duration includes the delay due to the UARTs, at the DC/LBR and SM/LR, which run at baudrate of 115.2 kbit/s and 9.6 kbit/s, respectively. Lastly, an IEEE 802.15.4 packet sniffer was used to measure the IP control traffic observed in the area near the LBR during almost 28 hours. DLMS rounds were made to all SM/LRs, following the same 30 minutes pattern between TCP and UDP of the previous DLMS tests.

IV. EXPERIMENTAL RESULTS

A. Hop distance between LRs and LBR

Fig. 3 shows the histogram with the relative frequency of each hop distance. The average distance is 3.06 hops. During the test, 95% of the time the LRs were at a distance not higher than 4 hops.

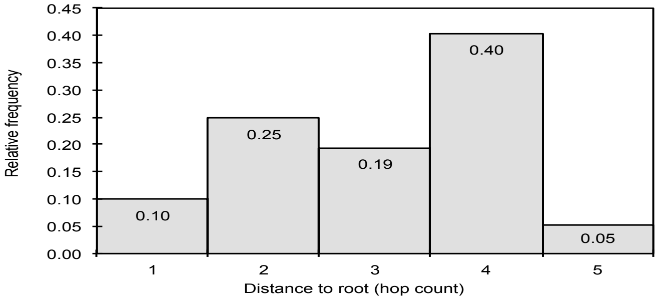

Fig. 3. Relative frequency histogram of the hop distance LR-LBR.

1) RTT and ping loss

Fig. 4 shows the variation of the average RTT and ping loss ratio of each round of pings over the test duration. The average RTT is near 50 ms almost all the time, with a slight increase near the end of the test, which is a good average value for a multi-hop network formed by nodes with low processing capacity, and is compatible with more demanding Smart Grid applications. The average ping loss ratio varies between 10% and 60%. These values were expected as well

(Lossy Network). The increasing ping loss over the test period was due to material, including metallic structures, being stored in the warehouse. It should be noted that (1) the network scenario was chosen to stress out the network solution and (2) the ping loss ratio does not indicate the end-to-end loss probability but the loss probability of the round trip, which is much higher than the one-way packet loss ratio. Fig. 5 show the RTT by distance CDF. As expected, the RTT increases around 15 ms per hop. Moreover, the RTT variation increases fairly with the distance: at 1 hop distance it is almost constant with the majority of RTT values below 20 ms, while at 5 hops the variations can reach 40 ms. All RTTs are below 160 ms. The average RTT is approximately the RTT with a 3 hop distance, which is consistent with the average hop count (3.06 hops), and is below 65 ms.

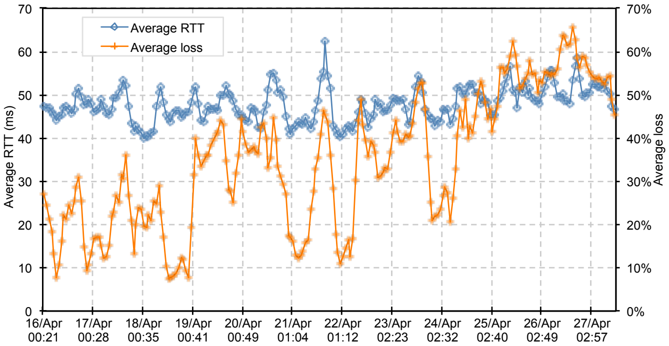

Fig. 4. Average RTT and ping loss ratio.

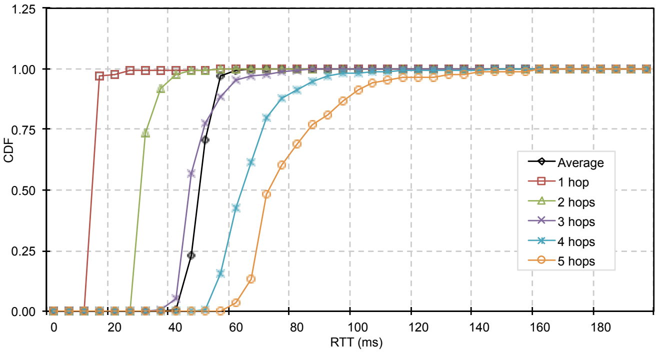

Fig. 5. CDF of the RTT as a function of distance (hop count).

Fig. 6 shows the CDF of the ping loss ratio as a function of distance. At a distance of 1 hop there is almost no loss. The ping loss ratio at a distance of 5 hops tends to be lower than at distances of 3 and 4 hops. This is due to the RPL approach of encouraging nodes to go up in the DAG, towards the root, but restraining them from going down to prevent loops. Nodes select parents upper in the DAG that have better ranking, but when the link quality degrades, nodes take some time for selecting a parent lower in the DAG. Therefore, since the link quality tends to vary along the day, many nodes that would be best served at 4-5 hops are temporarily served at 3-4 hops through worse links, thus presenting higher losses. Nodes at distance of 2 hops are less likely to present this behavior because there are less parent candidates.

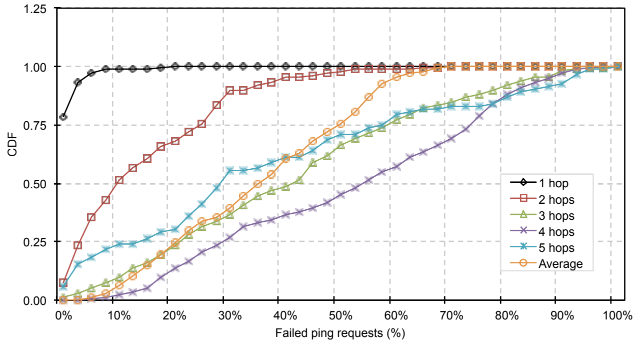

Fig. 6. CDF of the ping loss ratio as a function of distance.

TABLE I. DURATION OF DLMS SESSIONS

	Average	25th percentile	Median	75th percentile
TCP	779 ms	217 ms	243 ms	258 ms
UDP	695 ms	213 ms	237 ms	252 ms

2) Duration of DLMS sessions

Fig. 7 and Fig. 8 depict respectively the CDF of the duration of successful DLMS sessions, including UART delays, and the normalized histogram of the failed DLMS sessions per round, when using TCP or UDP as the transport protocol. Table I presents DLMS sessions duration. The UARTs, at both DC/LBR and SM/LR, add 57.8 ms to the DLMS request (64 bytes) delay, and 115.6 ms to the DLMS response (128 bytes) delay, thus adding a total of 173.4 ms to the duration of a DLMS session. The performance depends on the network but also on the configured timeout and number of retransmissions for TCP and UDP. Given the configured timeouts and maximum number of DLMS retransmissions, the maximum delay of a successful DLMS session is 45 s for UDP, and 120 s for TCP.

In Table I it can be seen that the duration of the DLMS sessions is roughly the same with TCP and UDP, with a median as low as about 240 ms. There is a difference of 12% in average values, mostly due to the longer DLMS timeout used with TCP (60 s) along with the variable timeout of the TCP itself that grows in case of congestion. Fig. 7 shows that more than 90% of the successful DLMS sessions ended under 400 ms (includes UART delays), 93.4% with TCP, and 94.6% with UDP. The 99th percentile is reached at 10400 ms with UDP, and 10800 ms with TCP. It must be emphasized that these results depend greatly on the DLMS timeouts and number of retransmissions configured for each transport protocol.

Regarding DLMS sessions failures per round, Fig. 8 shows that, with either TCP or UDP, less than 5% of the rounds had failed sessions. The average of failed DLMS sessions per round was just 0.25% for TCP, and 0.47% for UDP. As expected, more DLMS retransmissions means less failed DLMS sessions but also an increase of the overall DLMS session duration. DLMS applications with real-time requirements may decrease the number of maximum retransmissions or the timeout associated with the selected transport protocol.

These results show that the network solution along with the selected configuration are able to handle DLMS applications with requirements of low loss.

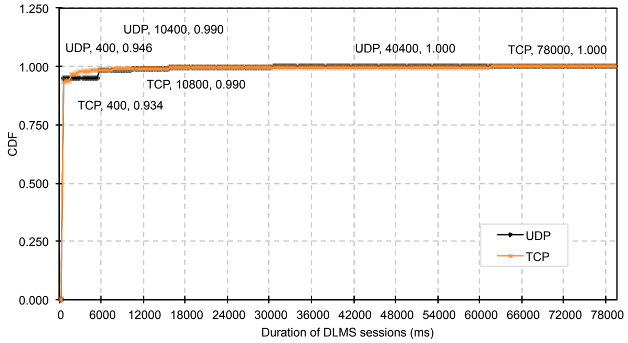

Fig. 7. CDF of the DLMS session duration, including UART delays.

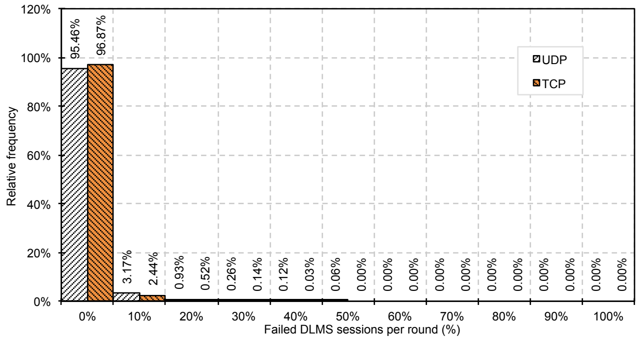

Fig. 8. Normalized histogram of the failed DLMS sessions per round.

3) *Control traffic overhead*

Fig. 9 shows the cumulative IP control traffic observed with an IEEE 802.15.4 packet sniffer, near the LBR. DLMS rounds were made to all SM/LRs, following the same 30 minutes pattern between TCP and UDP of the previous DLMS tests. The IP control traffic consists of all the ICMP messages, which are from the IPv6 Neighbor Discovery and RPL protocols. From the slope of the curve, it can be observed that the IP control traffic was almost constant, over 0.35 kbit/s, which represents only 0.14% of the selected data rate – 250 kbit/s. Although the observed traffic is from the medium near the LBR, it includes ICMPv6 messages, such as the Duplicate Address Detection, RPL DAO and DAO-ACK that are not only from LBR neighbors. Therefore, this measurement gives a good hint of the IP control traffic overhead in the network.

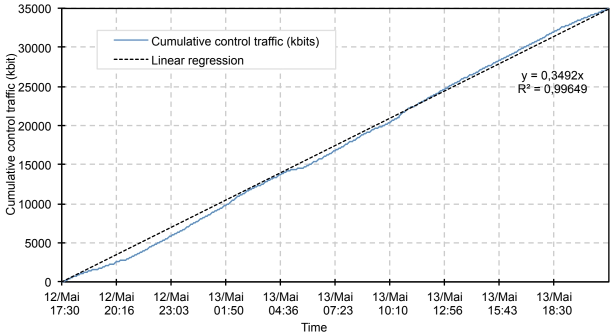

Fig. 9. Cummulative IP control traffic captured near the LBR.

V. CONCLUSION

We presented a multi-hop wireless networking solution for Smart Grid that relies on RPL, 6LoWPAN and IEEE 802.15.4g protocols. The solution was evaluated in an industrial environment using a DLMS/COSEM Smart Grid metering application. Experimental tests were done over a 20 days period. The results can be used as a basis to evaluate other 6LoWPAN/IEEE 802.15.4g networking solutions. We have shown that, as expected for this type of networks, the IP packet loss ratio increases severely with the hop distance, ranging from almost no packet loss at 1 hop up to a ping loss ratio of around 90% at distances of 4-5 hops. We also observed the impact of materials being stored in the warehouse on the ping loss and RTT over the test period. Overall, the RTT was low, increasing around 15 ms per hop. We have shown that albeit the high IP packet loss ratio, the average of failed DLMS sessions per round was just 0.25% for TCP, and 0.47% for UDP, making it suitable for applications demanding high success ratios. For applications not implementing DLMS retransmissions, TCP is the most suitable. Applications that require real-time communications at the expense of higher loss ratios might rely on UDP with fewer DLMS retransmissions. We have shown that more than 90% of the DLMS sessions were done under 400 ms, which includes a 173.4 ms delay of the UARTs.

The low control traffic overhead that was observed suggests that there is room for the network to scale up, possibly to a few hundreds SM/LRs, but distances higher than 4-5 hops need to be avoided. The scalability also depends on the application demands; the DLMS traffic pattern used in the experiments follow the round robin approach used by many operators but was more demanding than the typical smart metering application. Scalability might also be increased with more LBRs, even if sharing the same channel.

As future work we intend to test a network with one hundred LRs, and measure the power consumption of the LRs due to both control and data traffic, taking into account the type of DLMS/COSEM application.

ACKNOWLEDGMENT

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