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PLC sensor IPv6 networking interoperable with WSN

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Abstract

Technology evolution have made possible to connect all kind of devices to IP network. This becomes an evident objective for sensors networks research.

In this paper, we investigate the possibility of using IPv6 for sensor networks connected through powerline communication (PLC) non-wireless mediums and demonstrate possible interoperability.

Our work is based on the adaptation of the IEEE 802.15.4 standard protocol. It is constrained by the low-power, lossy and low data-rate context of powerline transceiver that uses pulse modulation.

Our aim is to provide interoperability features regarding others mediums with a robust and reliable communication stack for smart metering, home control or home area networks applications.

This document propose the first adaptation of the IEEE 802.15.4 commons standard on PLC medium. Following this standard interface, we demonstrate the possibility to carry out data on PLC with great reliability, and low power energy requirement using our WPCTM physical layer (standing for Watt Pulse Communication (WPC)).

Relying on this adaptation, we then focus on the convergence of the IPv6 protocol at the network level, with the 6LoWPAN adaptation. We also present our initial implementation of the RPL setup and routing protocol. This allows for a full network layer stack and results in efficient routing in our low power, low data-rate and lossy network context.

Thus, we finally demonstrate interoperability with a real testbed between powerline and wireless sensor networks running IEEE 802.15.4/6LoWPAN/IPv6/RPL stacks.

We conclude about the interest of such interoperability for the real usage of sensor networks with a feedback from field's applications deployment and our future work.

keywords

Sensor networks, PLC, 802.15.4, 6LoWPAN, IPv6, RPL, Adaptation layer, Interoperability .

1 Introduction

Since the emergence of the Internet, the meaning of the word " connectivity " entered in another dimension. The first step was the internet of the machine, where each of them, often computers, can be connected to the internet network. The second step was the internet of users, where each of them can act on the internet content. We are now at the internet of things, third step of the internet evolution, and focused on everything that could be connected, but is currently not. The word " things " employed here is voluntary vague, because it doesn't gives any restriction on the device that can be connected to the internet.

These three steps explains simply the explosion of the connectivity that rise up between 134 and 1,648% from 2000 to 2009 depending on the world region considered ¹.

In this context there is definitively a need for heterogeneity, and the use of open protocols, to enable the cohabitation between them and create a real interconnectivity through all these devices. We truly believe on the the use of open protocols compared to proprietary protocols, because it provides easy interfacing facility between devices. A proprietary approach sounds incompatible with our interoperability aim.

We assume that a single technology cannot fulfill every requirement, and that there will be always a need for using different technology together to cover all the needs that will appear in the future. With this assumption, we present here a way of providing a reliable and robust interoperability in a low power and lossy networks (LLN) context. In particular we focus here on the low rate wireless personal area networks (LR-WPAN), for which the IEEE 802.15.4 standard [10] has been designed. The vast majority of these devices are wireless and we brings here an easy interoperability feature on another medium using the powerline communication (PLC).

Most of the hard work done by 6LoWPAN for header compression for instance, would actually work quite well over other media. Moreover, great developments effort based on the IEEE 802.15.4 standard in the sensor networks field have been made in the wireless domain.

However, like every media, wireless communications have some limitations. In particular, the radio range is depending on the environment, and some elements (such as grounded metal) make the radio transmission collapse [2]. Reflections and absorptions may cause a reliable radio link become unreliable for a period of time and then being reusable again, creating lossy networks. Though, in a building or urban context, a reliable network is already installed and available : the power grid.

The grid is a good way to carry data through an entire building or town without being affected by obstacles such as walls, floors or even the weather, because there is always a physical link between each point of the network. From this observation, it seems obvious to propose powerline communication (PLC) into sensor networks efforts. Many PLC communication protocols exist, but many manufacturers have developed their own. Unlike PLC devices which aim to provide a high data rate (up to 200 Mb/s for Homeplug AV standard [6]), the transceiver that we studied works in the low data rate domain (less than 250kb/s) and aims to keep it power consumption, size and cost as low as possible. These features are rather similar to low rate wireless personal area network nodes (LR-WPAN).

With this assumption, we present here a way of providing a reliable and robust interoperability in a low power and lossy networks (LLN) context.

The paper is organized as follows : The section 2 defines the context and brings a short presentation of the PLC transceiver we used. It focuses on the main differences between RF and PLC from a MAC layer point of view and justify the need of an adaptation of the IEEE 802.15.4 standard over PLC. Section 3 explains the adaptation of this standard over PLC with the transceiver presented in the previous section. Sections 4 and 5 describe respectively the network and the routing part of the communication stack. The section 6 shows an heterogeneous experiment of the 802.15.4 adaptation over PLC with RF nodes. The section 7 focuses on a interoperability networking testbed. The section 8 concludes on our work and presents the future work provided by such an implementation.

2 Context

The IEEE 802.15.4 standard has been originally written for radio frequency (RF) devices, so it could be unusual to have a PLC device using this standard to communicate. To clarify this, a return to the standard rationale is needed: The goal of the IEEE 802.15.4 standard is to provide a common language through LR-WPAN. Unlike wireless local area networks (WLANs), WPANs involve little or no infrastructure. This feature allows small, power-efficient, inexpensive solutions to be implemented for a wide range of devices. A LR-WPAN is a simple, low-cost communication network allowing wireless connectivity applications with limited power and relaxed throughput requirements. The main objectives of an LR-WPAN are ease of installation, reliable data transfer, short-range operation, extremely low cost, and a reasonable battery life, while maintaining a simple and flexible protocol. IEEE 802.15.4 standard defines the protocol and compatible

¹<http://www.internetworldstats.com/>

interconnections for data communication devices using low-data-rate, low-power, and low-complexity for short-range RF transmissions in a WPAN.

The power consumption of these devices has to be low, because they are often on battery or must not create an overload of power consumption either for the appliances where they are embedded on the grid. These assumptions have a big impact on the communication system design, because every frame sent has a cost that has to be considered.

Moreover, typical applications such as smart metering, home control or home area networks applications do not require a big throughput. A few tens of kb/s is enough.

Our PLC transceiver is a low data-rate, low power and low cost communication technology, and many LR-WPAN features previously described corresponds to our PLC environment. The main difference is the media employed, which is used to communicate and either to power the node.

PLC nodes are therefore not constrained by the availability of energy because they have a reliable constant power source. This is the major difference with wireless nodes. But even if it is not restricted by the amount of power available, it is essential to keep the consumption of every node as low as possible for the smart home context. Using a few watts node consumption to control a few watts device is unwise. Powerline used as a media for communication provides a physical link between each node of the grid but the presence of a link does not mean that communication is always possible considering consumption, size, price and noise generated on the medium. Our approach is to keep these factors as low as possible. As well as WPAN, communication between nodes is not always possible from any point of the grid. Like RF nodes, which can reach only their neighbours in a restricted area, PLC nodes sometimes cannot reach some areas of the connected grid, depending on its topology and the loads connected.

There is local dynamic signal strength that provide a sort of mobility feature on the electrical grid, depending on the electrical activity on the grid. We can not avoid these perturbations due to real-life activity, and the communication has to adapt to them. The nodes being statics, this mobility might better be called reachability, regarding the position on the grid and the loads that can be plugged/unplugged on the grid at any time. The plugged/unplugged loads continually change the grid response and impact the communication possibilities on the medium. Therefore, PLC is facing to the same problem as WSN concerning the possible unreliability of their medium. IEEE 802.15.4 dedicated to PLC is a robust solution to low-rate communication over powerline. Associate to IEEE 802.15.4, it becomes an good way to provide an easy interoperability with LR-WPAN to merge the best of these two worlds and carry data on a heterogeneous low-rate PAN with a better reliability.

2.1 Wireless medium in LR-WPAN

The wireless devices using the IEEE 802.15.4 standard provide good mobility features, roughly limited by the zone of reachability of at least one of their neighbors. The principal limitation of these devices is the management of their power resource that is limited to the battery capacity or energy scavenging. The management of the energy available is really a key point for these devices, and is directly linked to the lifetime of the network. If a node is managing a lot of paths, the depletion of its power resource can shut-off the node and results in a possible unreachability of the network routed through this particular node. Many works aims to optimize the network lifetime by optimizing the power management with the use of duty cycling (in various MAC protocols such as S-MAC[18], T-MAC[16], or Z-MAC [13]), efficient algorithm design [15] or sink positioning [14].

2.2 PLC medium in LR-PAN

The powerline medium can't provide the same mobility feature as the wireless medium, because of the wire and the number of electrical outlets available. But the power resource management is not a problem, because the device is directly plugged in a power supply (except if the supply is not reliable). In PLC world, different coupling technologies exist that provide different networking characteristics such as data rates, transmission range, error rate with different needs in power load and different perturbation on the power line. We study in this paper testbed a low cost, low power and low rate technology very suitable for sensor networking on LR-PAN. The range provided by the PLC medium can reach up to 1 km in a urban context, regardless on the environment, but is depending on the electrical activity on the grid.

Table 1: Wireless vs Powerline medium

	RF	CPL
Mobility	+++ (no cord)	Limited to the cord
Power	Limited to battery	+++ (grid powered)
Range/loss	depends on nearby noise	depends on power grid noise

Table 1 compares these two mediums in a Low Rate PAN (LR-PAN) context.

Each medium can match different requirements. We see that they are both lossy but from different causes, and they completed well each other on other criteria. With an efficient use of a combination of these two mediums, we should be able to provide a very reliable solution. This implies the need for interoperability and/or cooperation between the different mediums available, and this is our goal in the following.

2.3 PLC technology

We first present the particular transceiver on which we rely. WPCTM[17] stands for "Watt Pulse Communication". It is a technology developed by Watteco², which enables to carry out any type of low data transfer communication with a reliable propagation and can be deployed on the same powerline network with other technologies without interfering. This transceiver is based on the transient behaviour of electrical networks. By using network reaction respect to load change, it is possible to create high level, low energy pulses (compliant with EMC regulation). As a result, the pulse magnitude can be significantly higher than noise even after propagation and ensure a robust communication signal. The coupling device is very simple and the network reacts with its own resonance ensuring a good propagation medium. This technology takes advantage of a physical natural phenomenon: the ignition pulse produced by appliances connected on an electric network. A pulse is a very short (a few nanoseconds) pulse produced by a load during its ignition or extinction and constitutes an unambiguous signature. The transceiver includes a microcontroller driving an adapted load, producing the pulse when connected to the mains. This pulse propagates over the power line at a long distance (up to 1 km in a public lighting environment). The emission of pulses can be triggered according to a controlled time schedule in order to communicate between two points of an electric network.

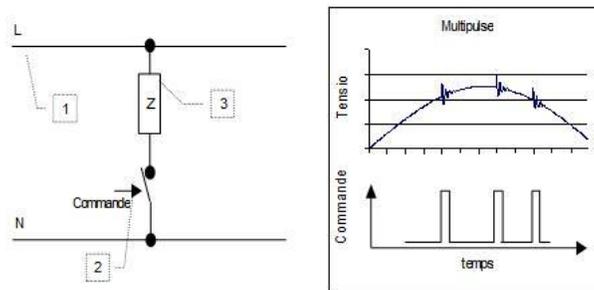


Figure 1: WPCTM communication principle

The chip has the following characteristics:

- A small size (approximately 500 mm²), induced by the network coupling method.
- A low power consumption (10 mW), due to the coupling method and the simplicity of the reception floor.

²<http://www.watteco.com>

- A reduced cost of electronics (i.e. dollars order for large quantities), induced by the communication with pulses. This allows simplicity for broadcasting data and front-end analogical receiver, limiting electronic components and signal processing.

As a "powerline modem", an OEM module can re-use any existing protocol, providing a powerline adaptation of the communication stack. In this paper we focus on the adaptation of the IEEE 802.15.4 standard protocol and show the possibility it offers for upper layers.

Table 2 outlines the main features of this PLC transceiver.

Data rate	10kb/s bi-directional
Digital Connection	Direct RX/TX or SPI serial mode
Frame Check and Correction	8 bits CRC and Hamming encoding
Input Voltage	110 to 230V, 50-60Hz
Power Supply	5V DC
Power Consumption	10mW average on communication

Figure 2: WPC Technical features

3 IEEE 802.15.4 adaptation over PLC

The IEEE 802.15.4 standard defines the PHY and MAC layers of the OSI model. In this paragraph, we propose to adapt these two layers on PLC. The original standard defines two different device types that can participate in a network: a full-function device (FFD) and a reduced-function device (RFD). The FFD can operate in three modes serving as a PAN coordinator, a coordinator, or a device. A FFD can talk to RFDs or other FFDs, while a RFD can talk only to a FFD. A RFD is intended for applications that are extremely simple, such as a light switch or a passive infrared sensor. Our PLC nodes can operate as a FFD or a RFD, depending on the embedded software .

3.1 RF transceiver emulation over PLC

Even if the scope of the standard is for wireless devices, we first investigated the idea of using it over raw PLC in [3]. Indeed we found that the definition of a LR-WPAN in the 802.15.4 standard is very close to our PLC testbed³.

For the adaptation of the IEEE 802.15.4 standard over PLC, an open IEEE 802.15.4 RF stack is used. The goal of this adaptation is to emulate a RF transceiver with the WPCTMtransceiver. To achieve this, an enhanced SPI interface has been developed between the WPCTMtransceiver and the microcontroller to drive it as a "regular" RF transceiver.

3.2 PHY adaptation

The PHY layer of the IEEE 802.15.4 standard provides the following services: activation/desactivation of the transceiver, Energy Detection (ED), Link Quality Indication (LQI), Channel Selection, Clear Channel Assessment (CCA), transmitting and receiving packets across the physical medium. The specific WPCTMtransceiver induces some timing adjustments because this transceiver transmits data only near the rising zero-crossing voltage while the reception is continuously possible.

The transceiver fragments every IEEE 802.15.4 frame in smaller packets. The actual data rate is about 10Kbits/s over 50Hz frequency, meaning that 25 bytes are sent every voltage period. Therefore the transceiver fragments data in 25 bytes packets sent near the zero crossing of the voltage. This specific communication introduces timing adaptations compared to a classic RF transceiver which has a continuous transmission. The

³The WPCTMtransceiver designed by Watteco (<http://www.watteco.com>)

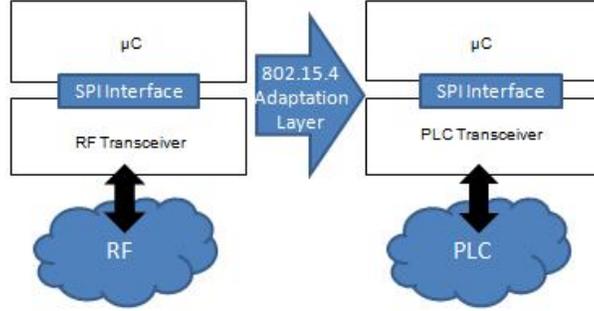


Figure 3: Emulation of a classic RF transceiver by a PLC transceiver through an enhanced SPI interface

PHY specifications of the IEEE 802.15.4 standard fully describes the physical interface (i.e. frequency band, modulation and data rate). For this specific transceiver, these specifications are reduced to minima. The attributes of the physical interface are written in the PHY PIB (PAN Information Base). This information base has been adapted to fit with our PLC transceiver.

- `phyCurrentChannel` : Unlike RF, there is only one channel available for our physical interface. The normalization for the different PLC frequency band is still in progress but a time slot in the 2-4 Mhz band has been already reserved for low rate PLC in the IEEE P1901 working Group [9]. This time slot is named "LRWBS" for Low Rate Wide Band Services and we use it to communicate.
- `phyTransmitPower` : This attribute is used to set the power of the transceiver transmission. The power transmission is constant for WPCTMtransceiver, so this parameter is set to a constant in accordance with PLC standards.
- `phyCCAMode` : This attribute specifies 3 different Clear Channel Assessment (CCA) modes, defined in the IEEE 802.15.4 standard. The CCA is performed with a specific method on WPCTMtransceiver.
- `phyCheckCRC` : This attribute is used to enable or disable the Cyclic Redundancy Check (CRC) checking. One CRC check is implemented in the WPCTMtransceiver so you can enable or disable this attribute.
- `phyGenerateCRC` : This attribute is used to enable or disable the Cyclic Redundancy Check (CRC) generate. One generation is implemented in the WPCTMtransceiver so you can enable or disable this attribute.

3.3 MAC adaptation

The MAC layer used over the WPCTMtransceiver is very close to the MAC layer defined by the standard. However this transceiver provides a 10 kb/s data-rate using a specific modulation and is quite different from a classical radio transceiver. As a result, it induces some adaptation with the MAC part to deal with the latency of the transceiver (due to the lower data-rate than classical 802.15.4 radio transceiver). A few timing adjustments are needed regarding the specific communication. The MAC layer of the IEEE 802.15.4 standard provides the following services: beacon management, channel access, GTS management, frame validation, acknowledged frame delivery, association /disassociation, security. Timing attributes defined in the MAC PIB were increased to fit with WPCTMphysical interface. The medium access we use is the carrier sense multiple access with a collision avoidance (CSMA/CA) as defined in the standard.

- `macAckWaitDuration` : This attribute determines the time limit from non-received acknowledge. This attribute has been incremented in order to respect the transceiver specificity. This incrementation is a result of the modification of the MAC constant "aUnitBackoffPeriod" which takes part of the "macAckWaitDuration" attribute's calculation. This constant determines the number of symbols forming the basic time period used by the CSMA-CA algorithm, which is used in our adaptation layer.

3.4 Results of the adaptation

Regarding LR-WPAN features defined by the IEEE 802.15.4 standard, we can compare them with a PLC network implementing our 802.15.4 standard adaptation.

Table 2: LR-WPAN vs WPC-PAN networks

	LR-WPAN [10]	WPC TM -PAN
Data rate	250, 100, 40, 20kb/s	10kb/s
Topology	Star, P2P, mesh	Star, P2P
Addressing	16b or 64b	16b or 64b
GTS	Optional	Not managed
CSMA-CA	yes	yes
Full ack	yes	yes
Low power	yes	yes (10mW)
RSSI	yes	yes (adapted to PLC)
Channels	16 in 2450 MHz band, 30 in 915 MHz, 3 in 868 MHz	1 channel in 2-4 MHz band

Our PLC adaptation clearly fits with the original definition of the IEEE 802.15.4 standard [10].

Moreover, the applications such as Home Area Networks, and Home monitoring targeted by PLC nodes are the same kind than WSN devices ones.

This adaptation provides a communication on powerline with the 802.15.4 data format. 2 shows the comparison between the definition of a 802.15.4 network as defined in the standard and a PLC network using our adaptation.

4 Network layer

In this section, we present the network layer of the communication stack and focus on the use of IPv6 (RFC2460) with the 6LoWPAN adaptation (RFC4944).

4.1 IPv6

The IPv6 protocol is designed as the successor to IPv4 and enables the Internet to scale for decades to come. To overcome the declining unallocated address space and in anticipation that networked appliances and instruments will outnumber conventional computer hosts, IPv6 extends the IP address space from 32 to 128 bits and directly addresses very important issues such as auto-configuration, security, multicasting, . . . This is especially welcome in the growing Internet of things we are speaking of. Recognizing the growth in link bandwidth in the wired Internet, IPv6 also increases the minimum MTU requirement from 576 to 1,280 bytes.

IP protocols are defined by the Internet Engineering Task Force (IETF) in the form of Request For Comments open standard protocols (RFC). These specifications provides a complete service for IPv6 networks and they were recently proven adaptable and operational for networking on small devices [7, 5, 8]. The IETF working groups about sensor activities started from these significant developments, by defining a way to carry the IPv6 MTU into smaller frames with RFC4944, security in RFC4301, autoconfiguration in RFC4862 and IETF drafts for routing and other aspects of the protocols.

As presented in [1], an IPv6 stack can be implemented in approximately 11.5 kilobytes of ROM and 1.8 kilobytes of RAM. With a complete run-time (timers, scheduler, etc.) as well as RFC-compliant UDP and TCP protocols above, an OS that provides a complete IPv6 network stack can be implemented within 35 kilobytes of ROM and 3 kilobytes of RAM. [8] pull down the memory requirement to 24 Kbytes of ROM

and 3.6 Kbytes of RAM. So complete IPv6-based applications can fit in a microcontroller providing only 64 kilobytes of ROM and 4 to 8 kilobytes of RAM which is the order of magnitude of today's microcontroller such as the PLC nodes we consider.

More than providing an efficient networking solution, the use of IPv6 on top of a PLC technology tackles the recurrent problem of proprietary protocol on this medium. We aim to provide the IP standard as it stands, without using costly gateways to connect PLC networks to the IP world.

4.2 6LoWPAN

With RFC4944, the IETF has defined the 6LoWPAN adaptation layer that includes a compression mechanism of the IPv6 header. This mechanism is stateless which means that it creates no binding state between the compressor/decompressor pair. Most of link technologies designed for smart objects do not support the full 1280-byte MTU that IPv6 require. For instance, IEEE 802.15.4 only supports 127-byte MTUs so a full IPv6 packet do not fit in an IEEE 802.15.4 frame.

6LoWPAN provides header compression to reduce transmission overhead, fragmentation to support the IPv6 minimum MTU requirement, and support for layer-two forwarding to deliver IPv6 datagram over multiple hops.

802.15.4 protocol data units have different sizes depending on how much overhead is present [10]. Starting from a maximum physical layer packet size of 127 bytes (`aMaxPHYPacketSize`) and a maximum frame overhead of 25 (`aMaxFrameOverhead`), the resultant maximum frame size at the media access control layer is 102 bytes. Link-layer security imposes further overhead, which in the maximum case (21 bytes of overhead in the AES-CCM-128 case, versus 9 and 13 for AES-CCM-32 and AES-CCM-64, respectively) leaves only 81 bytes available. This is obviously far below the minimum IPv6 packet size of 1280 bytes, and in keeping with Section 5 of the IPv6 specification (RFC2460), a fragmentation and reassembly adaptation layer must be provided at the layer below IP. Furthermore, since the IPv6 header is 40 bytes long, this leaves only 41 bytes for upper-layer protocols, like UDP. The latter uses 8 bytes in the header which leaves only 33 bytes for application data. Additionally, there is a need for a fragmentation and reassembly layer, which will use even more bytes.

This computation shows that without compression mechanism, a 802.15.4 frames would provide less than a quarter of its total size to the application layer. The 6LoWPAN mechanism is the results of a global reflexion about reducing the IPv6 header to complies efficiently with the 802.15.4 standard.

Drawing on IPv6 extension headers, it employs the header stacking principle to separate the orthogonal concepts and keep the header small and easy to parse.

To support the IPv6 1280-byte MTU, datagrams must thus be fragmented before they can be delivered to the link layer. Fragmented datagrams also provide additional opportunity for more effective buffering techniques when forwarding datagrams. For example, fragments can be delivered before a node reassembles the entire datagram, allowing nodes with severe memory constraints to forward complete datagrams.

5 Routing

The 6LoWPAN adaptation layer brings all the IPv6 mechanisms needed for large scale deployments and easy interoperability available for LR-WPAN with a minimum overhead. But these new IPv6-compliant nodes are very different from classic networking devices and routing over low power and lossy networks introduces requirements that existing routing protocols may not fully address.

Limited memory and communication capabilities constrain the routing state at each node as well as the routing information that might be communicated. These restrictions forbid the use of protocols that rely on complete link-state information. Traditional distance vector mobile ad-hoc networks (MANet) protocols are also unsuitable because most of them exchange route maintenance information at rates that exceed typical LR-WPAN communication and react to unreachability with expensive route-repair mechanisms. Instead, LoWPAN routing protocols must operate with incomplete information and tolerate some inconsistency.

The draft [11] provides a brief survey of the strengths and weaknesses of existing protocols and examines whether existing and mature IETF protocols can be used without modification in these networks, or whether further work is necessary. It concludes that no existing IETF protocol meets the requirements of this domain,

as existing protocols were not designed with all of the constraints of our context. They have made trade-offs which may or may not be appropriate for Low power and Lossy Networks (LLNs).

To achieve the design of this new routing protocol, a new IETF working group called Routing Over Low-power and Lossy networks (ROLL ⁴) was formed in 2008. This group has designed the IPv6 Routing Protocol for Low power and Lossy Networks (RPL) ⁵ that should be able to operate over a variety of different link layers, including but not limited to low power wireless or PLC technologies. Note that there is no "wireless" word in the name of protocol, because it does not rely on any particular features of a specific link layer technology. These features brings flexibility to the RPL protocol. This fits with our goal of providing interoperability in LLNs.

The ROLL working group has designed several drafts such as draft-ietf-roll-building-routing-reqs ⁶ and draft-ietf-roll-home-routing-reqs (RFC 5826), tightening the use of the RPL protocol in the application field of our PLC devices.

Figure 4 show an exemple of ROLL architecture. RPL enable Multipoint-to-Point (MP2P), Point-to-multipoint (P2MP) and a basic structure for point-to-point (P2P) traffic. The protocol model of RPL is based on the construction and the maintenance of one or several Directed Acyclic Graphs (DAGs). To achieve this, RPL defines DIO,DIS and DAO, three types of a new ICMPv6 message called RPL Control Message.

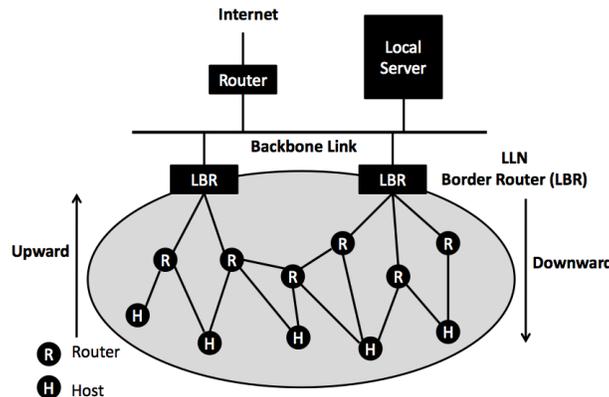


Figure 4: The ROLL achitecture

The RPL protocol is well suited for our PLC nodes for several reasons : This is a routing protocol specifically designed for LLNs, which is precisely our context. Indeed, it considers a set of constraints that were not in the motivation of other routing protocol [11]. This protocol is not related to a particular physical interface, so it is compliant with our PLC medium, and enable also to be used over others medium to create heterogeneous networks. The RPL protocol enable efficient MP2P traffic which is the principal data flows in smart-grid application. For example, all nodes will report their electricity, gas or water consumption at periodic times. RPL also provides efficient P2MP traffic which can be useful in the same smart-grid context to inform all nodes about power pricing informations and optimizing the energy consumption. It is also useful for street lighting application where a master will command all the lights from the street. RPL employs the trickle timer technique [12] that adapts the management traffic to the stability of the networks, and avoid greedy traffic to manage the network. RPL also allows mesh topology which increase our reachability capacity, and decrease the risks of unreachable zones on the power grid. The objective function concept offers a very wide range of applications, dealing with delay, power consumption or other metrics constraints independently from the physical layer used. Finally, RPL rely on the wide used IPv6 protocol which provide

⁴<http://tools.ietf.org/wg/roll/>

⁵<http://tools.ietf.org/wg/roll/draft-ietf-roll-rpl/>

⁶<http://tools.ietf.org/wg/roll/draft-ietf-roll-building-routing-reqs/>

an easy connection with many web applications. The security aspect is currently in progress in ROLL, and it is also an important feature needed for our applications.

6 Experiment

In this section, we present two different experiments relying on our adaptation of the IEEE 802.15.4 standard over PLC. First, a simple heterogeneous experiment between RF and PLC nodes. This is a first proof of concept of data transfers in a PLC/RF heterogeneous network. Such a MAC level experiment highlights a starting point of IEEE 802.15.4 interoperability. It doesn't implement the 6LoWPAN/IPv6/RPL part described above. The second experiment is an interoperability testbed, which is introduced in this section and will be presented in the next section. This experiment relies on the same 802.15.4 adaptation but implements the 6LoWPAN/IPv6/RPL part of the communication stack to show the extending possibilities of this adaptation.

6.1 Hardware

6.1.1 WSN Node

These nodes are used in the first experiment. These nodes are classic RF nodes from Crossbow⁷ composed



Figure 5: Tmote SKY platform from Crossbow

of a TI MSP430 microcontroller (8Mhz microprocessor, 48k Flash, 10k RAM), a TI CC2420 RF transceiver (2.4GHz ISM-band carrier, 250kbps) IEEE 802.15.4 standard compliant, and an on-board antenna. They can be powered by USB, or with 2 AA batteries. This enables the node to be autonomous and mobile. The USB interface is used as a serial link and can also be used to power the node. These nodes include also some sensors to measure temperature, humidity, and light. In this experiment, 2 Tmote SKY are used. The first one acts as a sender. It reads its own light sensor value and sends it in a IEEE 802.15.4 frame via its antenna. This frame is broadcasted each second. This node is battery powered and can be placed anywhere. The second one acts as a listener to transmit the light sensor value received on its antenna to its serial interface. This node is connected to the gateway with an USB connection which also powers it. This node acts as a RF/USB gateway.

6.1.2 PLC node

These PLC nodes are used in both experiments. The WPCTM technology, is used through a "WPC Development Kit" from Watteco. It enables users to easily integrate a WPCTM transceiver and to use it as an original communication tool on PLC.

It is composed of 4 different parts :

1. AC Power

⁷<http://www.xbow.com>

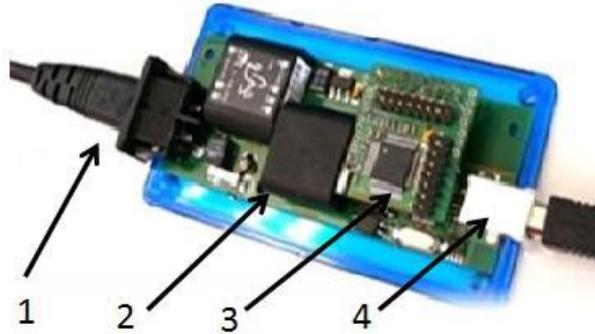


Figure 6: The WPC DevKit from Watteco

2. WPCTMtransceiver
3. Microcontroller
4. USB interface

The architecture is quite similar to a RF node which is basically composed of a microcontroller and a transceiver. Unlike RF nodes where the medium is the free space which does not need a connection, the WPCTMtransceiver needs to be connected to his medium through an electrical outlet. The USB interface provides a serial interface with the node. The USB part is opto-isolated from the high voltage part. In this first experiment, we used 2 PLC nodes with different configurations. The first one is a WPCTMDevelopment Kit connected to the PC gateway via its USB interface and connected to the grid, in order to send data over PLC. This device is used to relay the data sent from the gateway via the USB interface to the powerline medium. In a way, this device acts as a USB/PLC translator. The second one is a special form factor of the first node, with additionnal features. This device is called a "smartplug". It embeded a WPCTMtransceiver to communicate, control and command an electric relay to switch ON/OFF an electric device up to 16 amps, and an ADE chip to measure the electrical consumption of the device plugged into. A light bulb was plugged on this device to show the ON/OFF capability and create an electrical load to measure. This device acts as a light switch controlled by PLC, which is able to return some electrical consumption informations, the state of the switch, and an error message if the command fails.

6.1.3 Gateway

This gateway is used is the first experiment only. The gateway builds an IEEE 802.15.4 bridge between

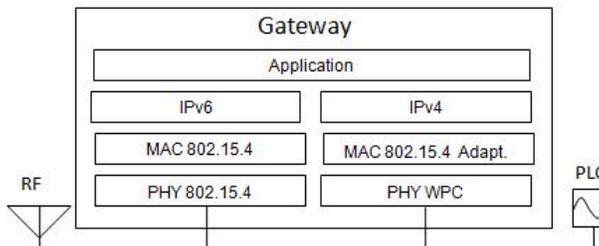


Figure 7: Gateway

Tmote SKY nodes and WPCTMnodes. As this first experiment is a proof of the concept, the gateway runs here on a traditional PC computer. This gateway reads the data sent by the Tmote SKY via the USB

interface, compares it to a threshold and send a command to the WPCTM module via another USB interface. The threshold is set to define a darkness or brightness state from the light value collected. The state defined is then converted into a command to carry over PLC, that will finally switch ON/OFF the light bulb. In summary, we built an elementary light switch actuator, controlled by a RF sensor node, and running over IEEE 802.15.4 standard protocol.

6.1.4 Low power development platform

This platform is used in our second experiment. To test our implementation, we used a low power PLC platform from Watteco. This platform brings the ability of manipulating safely (without the risk of high voltage) and reduces the medium as a short and simple wire to put away the possible perturbations of a real powerline medium in order to focus specifically on the stack performance. As shown in figure 8, our platform is made of a 220V/24V AC converter, 7 WPCDevKit and a 7 ports hub. Each PLC node of the platform has a strictly identical architecture as the WPCDevKit from Watteco. The WPCTM transceiver of each PLC node is driven by an ATmega 1281 or AT90USB1287 microcontroller, depending on the function intended. A connexion between all PLC nodes supply the power and provide the powerline communication medium (on 24V here). All nodes have a USB port to provide a serial interface. We use this interface to act on each node (to control the topology of the network for example) and bring back some debug informations.

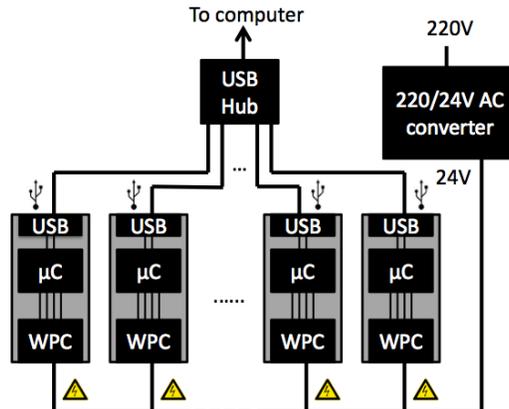


Figure 8: Low voltage PLC Platform

This platform will be connected to a RF network through a router in the interoperability experimentation.

6.1.5 Ethernet to PLC gateway

This gateway is used in the second experiment and is an evolution of the first gateway presented above. To provide the connection with our local PLC network, we developed a PLC to Ethernet gateway based on the Atmel RZUSBSTICK architecture. This device creates an ethernet over USB emulation. It is based on an AT90USB1287 microcontroller which drives the WPCTM transceiver the same way as the ATmega1281. This microcontroller is integrated on a separate PCB so that it can be plugged on a classic WPCDevKit. It avoids recreating a whole PLC node. This card directly integrates the USB interface with high speed isolators. With this card on the WPCDevKit, it allows a PC or a router to see our PLC node as an ethernet interface. Our PLC network is therefore seen as a subnet from the PC or the router connected.

This ethernet emulation has 2 main contributions: It creates a link with other networking devices, and it can be used as a sniffer on Wireshark⁸. The second capability is a major achievement because it enables the use of a performant network analyzer on PLC medium.

⁸<http://www.wireshark.org>

6.2 Software for heterogeneous experiment

The 2 Tmote SKY nodes are running under the Contiki 2.3 OS [4]. This contiki version includes an IPv6 stack with an implementation of 6LoWPAN which brings the nodes the capability of exchanging IPv6 packets over IEEE 802.15.4 standard. Thus, the light sensor value transmitted between the 2 Tmote SKY nodes is carried in IPV6 packets. The 2 PLC nodes are running under contiki 2.2 and the data transmitted between these nodes are carried in IPV4 packets. The first PLC node transmit the command received from the gateway into UDP format. The smartplug decodes the frame and perform an ON/OFF action on the bulb. This node then returns the electrical consumption of the load connected with an UDP frame. It is then decoded by the first PLC node which transmits this information to the gateway and plots the corresponding electrical consumption and the light value.

The gateway bridges PLC and Tmote SKY nodes at the application level. The software used in this experiment shows the data transmitted and provides a user interface to run the experiment.

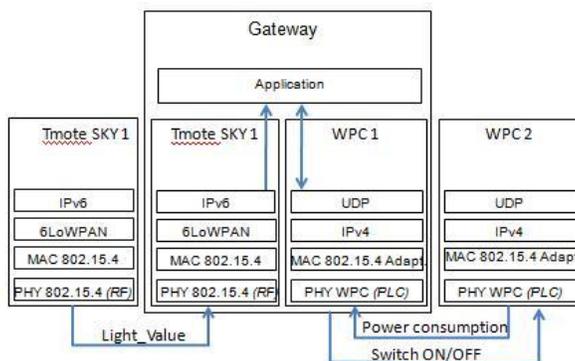


Figure 9: Communication layers

The first value read is above the switch off value threshold, so the bulb switch command is OFF. The gateway transmits the command to switch off the bulb and the switch state is set to OFF. When we hand seal the light sensor on the first Tmote SKY, the light value fall to a value which is under the switch threshold value. The gateway transmits a switch-ON command to the smartplug and the switch state comes up. The different frames exchanged during these actions are represented in 10 :

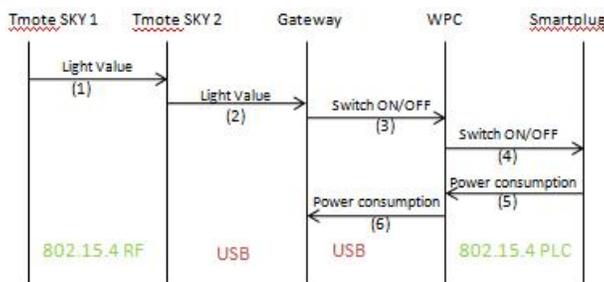


Figure 10: IEEE 802.15.4 frames exchange diagramm

7 Interoperability

7.1 Software for interoperability testbed

We describe here how we implement a communication stack following the previously described characteristics on our PLC testbed, and show a real interoperability testbed in the next section.

7.1.1 PLC node

Our stack is running under Contiki [4] in its 2.4 version ⁹. We use the uIP IPv6 stack from Contiki which implements a full IPv6 stack. We have created a specific PLC platform in Contiki 2.4. Because our transceiver is roughly a RF transceiver emulation, the major part of the adaptation on Contiki is in the MAC layer and the uIP stack don't need any modifications. Our implementation of RPL is the result of a collaborative work with SICS. We have implemented the HC06 draft ¹⁰ of 6LoWPAN and the version 5 of the RPL draft ¹¹. To performs our tests, we used the UDP sender and UDP client example available in the Contiki OS.

7.1.2 PLC gateway

There are 2 different softwares for this gateway. The first one creates an Ethernet emulation over USB and is derived from the RZUSBSTICK platform available in Contiki The second one is used as a sniffer application and has been developed in the 15dot4 tools project ¹² managed by Colin O'Flynn. Though this project is related to classic 15.4 RF nodes, the RF transceiver emulation of our specific PLC transceiver allow us to use this software over powerline.

7.1.3 PLC networking

We have first created a RPL network on our PLC platform. We used a node with an ethernet emulation as a sniffer with the Wireshark software. When we first plug a PLC node, it declared itself as a root because it get no response to its DIS RPL control message. When we connect other nodes, they received a DIO response from the root to their DIS request and declared themselves as leaf attached to the DAG. Through the serial interface on each node, we can send some commands and forces a node to drop the packet sent by another node. With these command, we can block the communication between a node and the root, to detach this node from the root. When the node send its DIS, it will only receive DIO from nodes and will associate to a node. As a result, this node will associate to the DAG with a higher rank than other nodes. This is a simple way for manually controlling the topology of the network and reproduce unreachability that can appear in real experiments. When the DAG is settled, we checked successfully the trickle mechanism on the DIO sending, with the doubling of the time after each expiration.

7.2 Interoperability Testbed

The interoperability experiment has been performed during an IPSO interoperability event ¹³ in March 2010. This was the first interoperability testbed between different RPL implementations. Eight companies took part in this event and five of them have tested their RPL implementations. We were the only one on PLC, the four others were using 802.15.4 RF nodes. These 5 companies used the same stack architecture, based on 802.15.4, IPv6 with 6LoWPAN (draft-ietf-6lowpan-hc-06) and RPL (draft-ietf-roll-rpl-05), but each had its own implementation, differing in the OS and the devices used. The bridge between the different participant was made at the IP level by a router where a RPL implementation was running.

As we can see on the set-up picture, the network formed was using three different media : Low-power PLC, RF (802.15.4) and Ethernet. The M-router 1 was set as the Dag root. Each router or node connected

⁹<http://www.sics.se/contiki/>

¹⁰<http://tools.ietf.org/html/draft-ietf-6lowpan-hc-06>

¹¹<http://tools.ietf.org/html/draft-ietf-roll-rpl-05>

¹²<http://sourceforge.net/projects/dot4-tools/>

¹³<http://www.ipso-alliance.org>

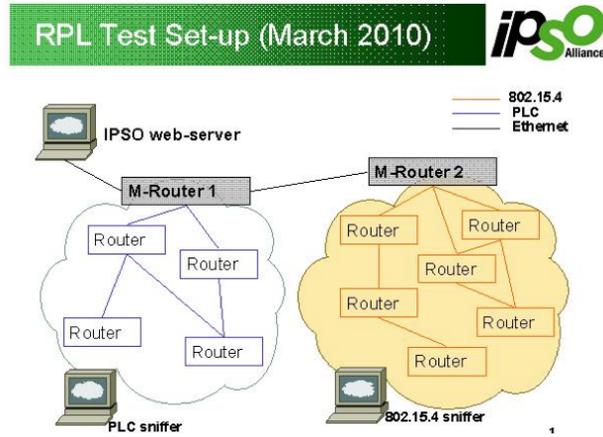


Figure 11: Interoperability test setup

was then associated to the DAG with a classic DIS/DIO exchange. As a result, the M-router 2 associated as a node, and our PLC nodes associated to this router. The RF nodes attached directly to the M-router 1. The Dag root has a `aaaa::1` address and all the nodes (RF and PLC) have a unique global address based on their EUI-64 with a `aaaa::/64` prefix.

After DAG settings, we were able to ping the node from each participating company with their global addresses from our PLC nodes. The others participants were also able to ping our node with the use of their global addresses. We also had set up one of our node as a DAG root, so that the M-router 2 and one of our node associated the DAG as leaves. This simple topology allowed us to make a ping from a PLC node to another PLC node through an ethernet link, and simulate the connection between two PLC network through a classic ethernet link.

We also performed successfully a global repair, where the DAG root increments its instance ID and every node from the DAG has to adopt this new instance ID. This testbed showed that our stack was able to easily take part of a heterogeneous network, in a LLNs context with the use of open standard protocols.

8 Conclusion

The IEEE 802.15.4 standard implements many primitives which provide a very complete service in highly constrained network such as LR-WPAN. In this paper, we explored the similarities between LR-WPAN and WPCTM-PAN and showed a simple adaptation layer of the IEEE 802.15.4 standard over PLC to extend the scope of LR-WPAN. With our adaptation, a large part of the IEEE 802.15.4 stack is implemented over PLC, with the use of the WPCTMtransceiver. The MAC/PHY primitives implemented with this adaptation provide a comprehensive IEEE 802.15.4 service over PLC which extends this medium to the IP world with the use of 6LoWPAN. It is a first implementation of a low power IEEE 802.15.4 network over PLC, which is extended to IP applications.

Because our work relies on protocols that are currently drafts and not RFCs (6LoWPAN HC06 and RPL-05), trivial future work will include updates from these drafts until they become RFCs, especially the RPL draft. This draft still need further revisions for improvements in the DAO mechanism and the security part. As described in the draft, RPL only defined a core set of functionalities and is not related to any particular technology. This is a strong point for the flexibility, but this also means that it let a part of the work to the implementation. The first experiment presented in this paper stands as a first interoperability testbed that is very hopeful, but it needs further work to be optimized on our network. Work still needs to be done, to tune the RPL protocol in a way that fulfill more restrictive requirements, without overpassing our node capacity. The Objective Function (OF) mechanism is also a very appreciable mechanism in RPL that we need to consider in our future work, to create a specific adaptation related to our PLC network. The results of the first interoperability event with RPL that we presented brings a good feedback about

the capabilities of this protocol, at least on small networks. We now need further experimentation to push the capabilities of each implementation with more complex functionalities. The next testbed will certainly include more companies and more diversity, which will enhance the interoperability aspect. Another part of our future work will be to test our stack on real applications, to measure the efficiency of the implementation, in comparison with the non-standardized protocol currently deployed. Finally, we plan to implement our stack and the specific WPCTM transceiver in a simulator, to focus on specific points that could improve the stack. We will test the performance of the stack with a homogeneous/heterogeneous dense network, and measure how far we can go on the scalability side with our actual implementation.

With this work, it is now possible to create an heterogeneous PLC/RF network in a LLNs context with the use of open standard protocol. More than dealing with coexistence, we now enable cooperation between these mediums, which is a major improvement. We have presented all the protocols of the communication stack from the physical to the network layer, including routing, to achieve the implementation of a communication stack over PLC for multi-physical layer IPv6 Networking. We have justified the need of these protocols for our LR-PAN context on powerline communication. Our experiments during the interoperability event has shown that our stack was able to interoperate with RF 802.15.4 nodes, with a bridge at the IP layer, creating a multi physical medium low power personal area network.

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