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A4WSN: An Architecture-driven Modelling Platform for Analysing and Developing WSNs

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Abstract This paper proposes A4WSN, an architecture-driven modelling platform for the development and the analysis of Wireless Sensor Networks (WSNs).

A WSN consists of spatially distributed sensor nodes that cooperate in order to accomplish a specific task. Sensor nodes are cheap, small, and battery-powered devices with limited processing capabilities and memory. WSNs are mostly developed directly on the top of the operating system. They are tied to the hardware configuration of the sensor nodes and their design and implementation can require cooperation with a myriad of system stakeholders with different backgrounds.

WSNs peculiarities and current development practices bring a number of challenges, ranging from hardware-software coupling, limited reuse, and late WSNs quality property assessment. As a way to overcome a number of existing limitations, this study presents a multi-view modelling approach that supports the development and analysis of WSNs. The framework uses different models to describe the software architecture, hardware configuration, and physical deployment of a WSN. A4WSN

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allows engineers to perform analysis and code generation in earlier stages of the WSN development life cycle. The A4WSN platform can be extended with third-party plugins realizing additional analysis or code generation engines.

We provide evidence of the applicability of the proposed platform by developing PlaceLife, an A4WSN plugin for estimating the WSN life time by taking various physical obstacles in the WSN deployment environment into account. In turn, PlaceLife has been applied on a real-world case study in the health-care domain as a running example. A case study based on home automation is presented as well.

Keywords MDE · Software Engineering · Software Architecture · Wireless Sensor Networks · Performance Evaluation

1 Introduction

A recent study predicted that in 2020 there will be 50 billion devices connected to the Internet [20]. These are devices capable of performing various operations, such as sensing data, actuating on the external environment, and so on. With this perspective, WSNs are becoming an important part of a wide variety of applications and systems including environment monitoring, energy metering, smart cities, health care and intelligent houses [59].

Wireless sensor networks are composed of low-data rate, low-cost and battery-operated wireless components called *sensor nodes*. A sensor node is a small digital device with communication, sensing, and limited processing capabilities. WSNs can range from small scale networks such as body sensor networks with few nodes [73], to large scale networks such as smart city applications with thousands of sensor nodes [23].

Despite the increasing usage of WSNs in modern applications, their development is still plagued by the following issues: (i) development is still performed directly on the top of the operating systems and relies on individuals hard-earned programming skills across all levels of the protocol stack [46]; (ii) WSN engineers must address challenging extra-functional requirements such as performance, security, energy consumption, with poor support for early testing, debugging, and simulation of WSNs in an integrated fashion [30]; (iii) in order to achieve high level of efficiency, the software of a WSN application is tied to specific hardware platforms, hampering the reuse of source code and software components across different projects or organizations [46]; (iv) due to the intrinsic multidisciplinary nature of the WSN problem space, WSN engineers must continuously collaborate with a high number of system stakeholders (e.g., users, application domain experts, hardware designers, and software developers) with different background and training [59].

To tackle the aforementioned issues, the WSN community is becoming aware of the need of using software engineering approaches in order to support the design, analysis, simulation and implementation of WSNs [72, 55].

This research proposes a novel modelling and analysis platform to support an architecture-driven development of WSNs. The platform is called A4WSN[1] and is

[1] It stands for **A**rchitecting platform for (**4**) **W**ireless **S**ensor **N**etworks

based on a multi-view architectural approach [33] based on three modelling languages to describe a WSN from different viewpoints: (i) software components and their interactions, (ii) the low-level and hardware specification of sensor nodes, and (iii) the physical environment where sensor nodes are deployed, separately. Model-driven engineering (MDE) techniques and tools are used to implement the modelling framework through metamodelling, model weaving, and model transformation. The modelling framework is supported by a programming framework that enables the implementation of analysis and code generation plugins by third party developers; they can be employed to assess and analyse the architectural design decisions, and generate executable code, respectively.

The whole A4WSN platform is realised by exploiting advanced MDE techniques, such as metamodelling, model weaving and model transformation. MDE allows us to define the modelling languages of A4WSN in a seamless and well-disciplined manner, and to realise the A4WSN programming framework so that it supports extensibility and customisation by design. The platform is available at the project website[2], it has been downloaded 141 times (according to Google Analytics up to February 2017), and for the last two years it has been used in our software and system architecture courses. We provide evidence on the applicability of the proposed modelling approach and on the extensibility of its programming framework by developing an A4WSN plugin called PlaceLife. Placelife analyses A4WSN models of a WSN and automatically assesses the lifetime of the network.

PlaceLife uses the A4WSN physical environment model that includes physical objects and material, thus providing an accurate WSN lifetime estimation. The *PlaceLife* plugin has been applied to a realistic home automation case study. The scenarios that can be considered using A4WSN are more realistic compared to existing simulation tools for WSNs, since the existing tools consider simplified models of the environment (e.g., a free space model) due to the limitations stated above. In a previous work [19] we made the first exploration for the feasibility of the modelling and analysis platform, with special emphasis on energy consumption analysis. In that work, the proposed modelling languages and the programming framework were not mature yet. The main contributions of this paper can be summarised as follows:

– a multi-view modelling platform for engineering WSNs is presented in detail (including a specification of the software architecture, low-level and hardware specification, and physical environment);
– a programming framework is provided which enables the development of plugins realising new code generation and analysis engines;
– the full development of the A4WSN prototype tool[3] that implements the proposed approach. This implementation is based on the Eclipse platform and can be integrated with other MDE technologies already available in the Eclipse community;
– the implementation of the *PlaceLife* plugin that can be used for the prediction of the WSN lifetime. This is a novel tool that incorporates the physical environment (together with other factors) into the model in order to have better prediction.

[2] URL: http://a4wsn.di.univaq.it/
[3] A4WSN prototype: http://a4wsn.di.univaq.it

The rest of the paper is organised as follows. Section 2 provides background information on WSNs, as well as the motivational example used throughout the paper. Section 3 provides an overview of the A4WSN platform. Section 4 describes the proposed modelling languages for WSNs, while Section 5 presents the programming framework. Section 8 presents the technologies used to implement the A4WSN platform. Section 6 focusses on the PlaceLife analysis plugin. Finally, Section 7 presents related work, while the paper concludes in Section 8.

2 Background and Motivational Example

This section provides a background on wireless sensor networks, considerations to motivate the need of our approach, and introduces the case study used throughout the paper.

2.1 Background on Wireless Sensor Networks

WSNs consist of spatially distributed sensors that cooperate to accomplish some tasks. Sensors are small battery-powered devices with limited processing capabilities and memory. Currently, the processor frequency of WSN nodes range from 4MHz to 32 Mhz while the nodes have two Kb to 412 Kb memory capacities [46]. They can be easily deployed to monitor different environmental parameters such as temperature, movement, sound, and pollution. Sensors can be distributed on roads, vehicles, hospitals, buildings, and people in order to enable different applications such as medical services, battlefield operations, crisis response, disaster relief, and environmental monitoring.

WSNs can be *event-driven* or *continuous* operation types. Event-driven WSNs report data to the base station (BS) only when certain events such as intrusion and fire detection occur. Continuous WSNs report data to the BS at regular intervals. Patient monitoring and temperature control are examples of applications that use continuous WSNs. In communicating data to a BS either single-or multi-hop topology can be used. When single-hop topology is considered, the nodes communicate with the BS directly whereas in multi-hop, some of the nodes may act as intermediate routers forwarding information on behalf of other nodes besides the usual sensing responsibility.

The unique characteristics of WSNs introduce new challenges [67] in different fields such as programming, security and software engineering. Researchers need to face limited sensor resources in terms of computation capabilities and memory as well as the limited lifetime of the sensors.

2.2 The WSN challenges and concerns

The issues outlined in Section 1 bring a number of WSN design and development challenges. This section describes some of the most relevant challenges which can be solved by abstraction and modelling. A summary of how the A4WSN framework

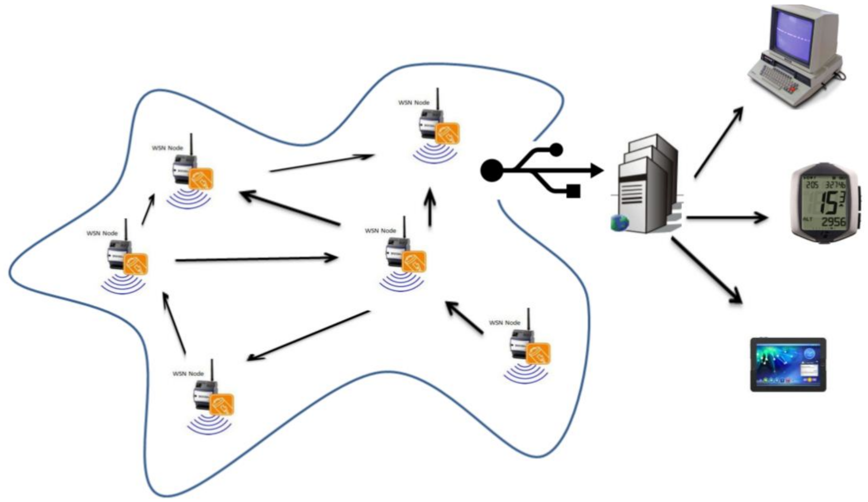

Fig. 1 Typical Architecture of a WSN Application

addresses these issues is presented in Section 3.

Abstracting implementation details into a design view: the development of a WSN application requires skills across all levels of the communication stack. A WSN application developer has to be knowledgable on programming as well as all the layers of the ISO/OSI reference model. Beside programming abstraction, abstracting an implementation view into an architectural design is a well known need. As stated in [55], *"end users require high-level abstractions that simplify the configuration of the WSN at large, possibly allowing one to define its software architecture based on pre-canned component"*. Abstraction is fundamental for future WSN development, since sensors and WSNs in general are becoming important components in pervasive computing, and mobile systems, with new types of stakeholders (e.g., mobile systems engineers, developers) and reduced domain-specific technical skills. Under this perspective, approaches for abstracting the implementation details from the underlying hardware and physical infrastructure are strongly advised [46, 8]. However, when current practices on WSNs are considered, the lack of engineering methods and techniques to manage these challenges is evident. Some initial effort has been made for architecting WSNs [37, 28], and this paper goes along that line providing more advanced solutions. A thorough comparison with related work is provided in Section 7.

Increase reuse: State of the art approaches mostly mix together software, hardware, and networking perspectives during the coding or design phase. Hardware and software components are locked and tied down to specific type of nodes, thus hampering the reuse of source code and software components across different projects or organizations [46].

Early WSNs quality property assessment: In traditional implementation-specific approaches engineers might afford to take structural and behavioural decisions at deployment time. However, in WSN development it is important to take those sensible decisions as early as possible, enabling the earlier and predictive analysis of both functional and extra functional properties. This possibility becomes especially valuable in all those cases where the sensor nodes cannot be easily accessed once deployed (e.g., WSN nodes embedded into concrete walls or WSNs deployed in hostile environments).

In addition to challenges, while designing and implementing a WSN, engineers and developers may face various concerns such as application energy efficiency [19], dependability [4], coverage [29], networking and communication, and performance.

In order to address the aforementioned challenges and cover the outlined concerns, we developed A4WSN, an architecture modelling platform that uses different models for specifying WSNs. It provides a design view of the system, and hides low-level details and complexities. A4WSN, being a multi-view approach including different models which cover different concerns, increases **separation of concerns** favouring the possibility of **reusing** software and hardware components across projects and organisations. A4WSN enables **model-based analysis** techniques and favour the earlier, predictive, analysis of both functional and extra functional properties.

2.3 The healthcare system case study

In this paper the healthcare system case study is used as running example in order to help the reader in understanding the main concepts and design decisions considered when engineering the A4WSN modelling languages. A case study based on home automation is also presented in order to show the effectiveness of the architectural approach and the PlaceLife plugin.

Recent technological advancements in WSNs have opened up new prospects for a variety of applications, including healthcare systems [36,3,66]. WSN implementations on pervasive computing based healthcare systems avoid various limitations and drawbacks associated with the wired sensors providing a better-quality of care, quicker diagnosis, more intense collection of information and at the same time keeping the cost and resource utilisation to minimal. Monitoring facilities introduced by using WSNs are particularly useful for early detection and diagnosis of emergency conditions, as well as keeping track of the diseases. WSN based healthcare systems are also useful for providing a variety of health related services for people with various degrees of cognitive and physical disabilities [2].

In the context described above, the case study (see Figure 2) represents the concept of an in-hospital WSN that allows monitoring patients' conditions with the help of pulse-oximeters. The monitoring system consists of two types of nodes: a monitoring station, and seven oximeter nodes, forming a star-network. Each pulse-oximeter monitors a patient continuously and a measurement is sent to the monitoring station

[4] http://www.dependability.org/

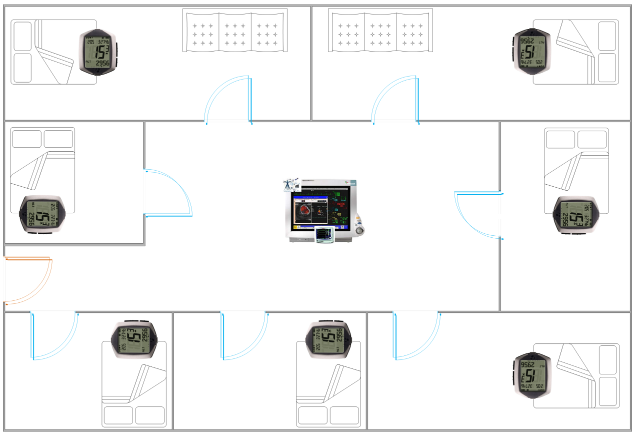

Fig. 2 Hospital scenario considered: i) the central component represents the monitoring station, ii) a pulse-oximeter is included in each room around the central one.

every three seconds. In case the oximeter reads a value below a threshold, an alert message is sent to the monitoring system, and the system goes into a *warning* mode in which sensor readings are sent to the monitoring station more frequently (i.e., once every 200 milliseconds), hence facilitating continuous monitoring of patients and allowing real-time responses in case of emergency conditions.

3 Overview of the Platform

In this section we provide an overview of the A4WSN platform. This research takes advantage of MDE techniques to support an architecture-driven development and analysis of wireless sensor networks. Figure 3 shows the main components of the framework: the *WSN modelling environment* for describing the architecture of a WSN, and the *programming framework*.

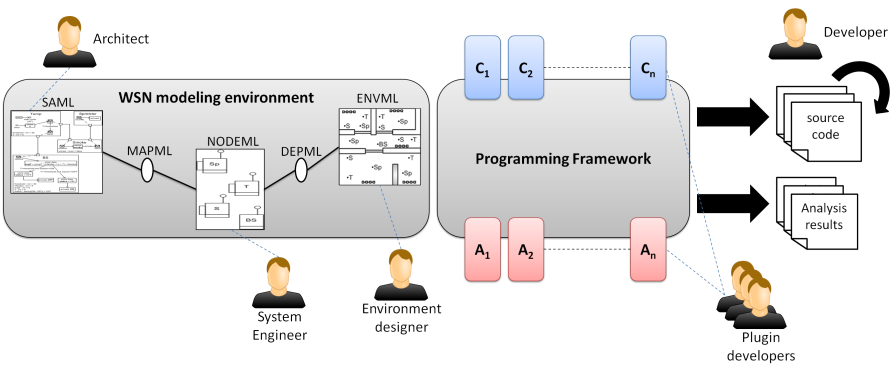

Fig. 3 Overview of the A4WSN platform

The **WSN modelling environment** exposes three modelling languages for describing specific architectural views of a wireless sensor network: the *Software Architecture Modelling Language for WSN* (*SAML*), the *Node modelling Language (NODEML)*, and the *Environment Modelling Language (ENVML)* (see Figure 3).

– The **SAML** language focuses on the *application layer* of the WSN. It is used to break down the application into a set of software entities (e.g., components), to show how they relate to each other, to better reason on their distribution throughout the network, and to reason on the business logic of the WSN.
– The **NODEML** language concerns the low-level aspects underneath the application layer of the WSN. In this context, stakeholders reason about routing protocols, middleware, hardware configuration of the nodes, etc.
– The **ENVML** language is about the physical environment where the WSN will be deployed. This viewpoint could be specially useful for developers and system engineers when they have to reason about the network topology, the presence of possible physical obstacles (e.g., walls, trees) within the network deployment area, and so on.

The three proposed modelling languages are linked together via two auxiliary modelling languages in order to create a combined software, nodes, and environmental view of a WSN. These languages are called Mapping Modelling Language (**MAPML**) and Deployment Modelling Language (**DEPML**), and they link together SAML to NODEML and NODEML to ENVML, respectively (see Figure 3). More specifically, the MAPML modelling language weaves together an SAML model and a NODEML model. It allows designers to define a set of mapping links, each of them weaving together components in the SAML model and node definitions in the NODEML model. The DEPML modelling language weaves a NODEML model to an ENVML model. A DEPML model allow designers to consider each node type defined in the NODEML model and to *instantiate* it in a specific area within the physical environment defined in an ENVML model. Each node configuration in NODEML can be instantiated *n* times within a specific area in ENVML with a certain distribution strategy.

Those two auxiliary modelling languages are used for a clear *separation of concerns* and duties while architecting the WSN (e.g., a software architect can focus on the application layer in the SAML model only, while a system engineer may focus on the nodes configurations in the NODEML model) and making the models *reusable* across projects and organisations. The main concepts of each modelling language are described in Section 4.

The **programming framework** (see Figure 3) provides a set of facilities for supporting the development and integration of *code generation* and/or *analysis* engines. In Figure 3, C_i and A_i represent code generation and analysis engines, respectively. The proposed programming framework knows at runtime which plugins are installed into the framework, and automatically provides the user with the available target implementation languages or the available analysis techniques.

Code generation and analysis plugins are structurally similar. An analysis plugin manages the analysis of WSNs (e.g., coverage, connectivity, energy consumption analysis), instead of a code generation plugin which is tailored to the generation of implementation code conforming to a set of specific target languages. More specifically, in A4WSN the main difference between code generation and analysis plugins resides in their returned output: the main output of a code generation engine can either be a set of source files, or binary packages, whereas the main output of an analysis engine can be a violated property, a counter-example, a set of numerical values, and so on. The detailed description of the programming framework is presented in Section 5.

The A4WSN platform is generic since it is independent from the programming language, hardware and network topology. Starting from a set of models (each one reflecting a certain WSN viewpoint), the code generation and analysis components can be plugged into the framework for generating executable code or analysing outcomes.

4 The Modelling Environment

As shown in the previous section, the modelling environment is composed of three main languages, which are SAML, NODEML and ENVML. Each language allows the user to frame the problem of describing the architecture of a WSN from a specific viewpoint [33]. It is important to point out that the modelling environment has been realised by: (i) carefully and extensively checking the state of the art in WSN development and modelling (see Section 7), and (ii) discussing with WSN and embedded systems engineers with many iterations of changes. We formalise the structure and concepts of all the modelling languages of A4WSN by defining their underlying metamodel (see Appendix A). In the next sections each modelling language is discussed. For the sake of brevity, we do not describe in details each element of the A4WSN modelling languages, they are presented in a dedicated technical report available online [38].

4.1 Software Architecture Modelling Language (SAML)

The SAML modelling language allows architects to define the software architecture of the WSN application.

The **software architecture** of a WSN is defined as a collection of software **components** and **connections**. Components interact with other components through (input or output) **message ports**; they specify the interaction points between a component and its external environment. Communication happens by message passing. The actual communication method of a message (i.e., broadcast, multicast or unicast) is specified in the send message action described later in this section. In this context, a **connection** represents unidirectional communication channel between two message ports of two different components. The data contained in a message is accessible by specific actions and events defined in the behaviour of the involved components.

Figure 4 shows the SAML model of the WSN of the hospital scenario introduced in Section 2.3. It is important to note that this figure is actually a screenshot of the real A4WSN tool available at: http://a4wsn.di.univaq.it. From a structural point of view, the whole WSN is composed of two main components: the *Oximeter* component represents the software running on each oximeter node, while the *Monitor* component represents the software running on the monitoring station.

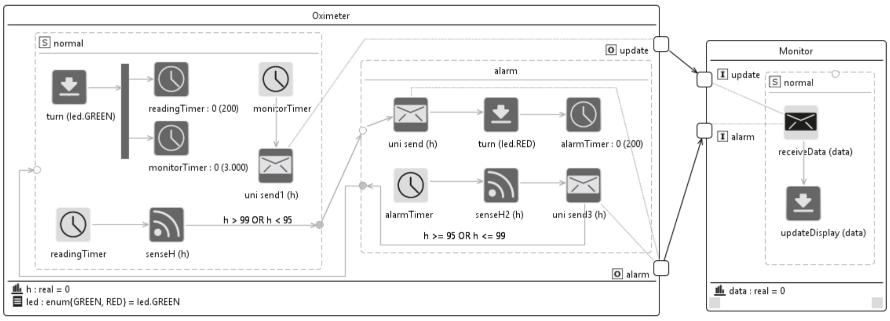

Fig. 4 Software architecture of the hospital scenario WSN

The internal state of a component is represented by the values of its **application data** and its current behavioural **mode**. An application data can be seen as a local variable declared in the scope of the component; application data are manipulated by actions, events, and conditions defined in the behaviour of the component.Application data can be either primitive (e.g., integer, boolean) or structured (e.g., enumeration, array, map). The *Oximeter* of the hospital scenario stores the current percentage of oxygen in the patient's blood as a real number in the *h* application data, and the current state of its status led in the *led* application data, which can be either RED or GREEN. A **mode** represents a specific status of the component at the application layer. At any given time, one and only one mode can be active in a component. The component reacts only to those events which are defined within its currently active mode. Each mode can contain a set of behavioural elements that represent actions, conditions and events which together make up the control flow within the component from an abstract point of view. Actions and events are connected via **links** representing the control flow among them. Optionally, a condition can be specified in a link, meaning that the behavioural flow goes through a link only if its condition evaluates to true.

An **action** represents an atomic task that can be performed by an SAML component. It is important to describe a new kind of action introduced called *scoped send message*; basically, this action tells that the set of nodes receiving the message is computed at run-time, depending on the value of a boolean expression; only the nodes whose application data values satisfy the boolean expression will receive the specific message, thus enabling dynamic scope-based interactions within the WSN [45]. For example, a scoped send message may be used in order to send a message to all the nodes whose *floorName* application data is equal to "*ground*" and whose *temperature* application data is greater than 21 degrees.

An **event** is triggered in response to either an external stimulus of the component (e.g., the message reception on a input message port), or some internal mechanism of the component (e.g., a timer fired). Examples of event include: entering a specific mode, receiving a message at a given port, an activation of a timer, the receiving of a call from an external service, the receiving of an interrupt from either a sensor or an actuator, etc.

By considering the *Oximeter* component of the hospital scenario, at startup it turns the led into green via the *turn(led.GREEN)* actuate action and starts two cyclic timers in parallel. Every time the *monitorTimer* is triggered (every 3000 milliseconds), the component sends the current value of the *h* application data to the *Monitor* component via the update message port. When the *readingTimer* is triggered (i.e., every 200 milliseconds), the component senses the current oxygen percentage in the patient's blood via the *senseH* action: if the read value is not below or above the norm (i.e., if it is not between 95% and 99%), then the component switches to the *alarm* mode. In this specific mode, the component firstly sends the current read value to the Monitor component via a dedicated *alarm* message port, then it turns the led into red, and starts a new cyclic timer with a period of 200 milliseconds. From this point onwards this component senses the percentage of oxygen in the blood of the patient and sends it to *Monitor* every 200 milliseconds. If the read value comes back in the acceptable range, then the component switches back to the *normal* mode. The *Monitor* component is straightforward. It has a single operating mode in which every time a message from the *Oximeter* component is received, its data is shown on a display via the *updateDisplay* actuate action. This component temporarily stores the value received by the various oximeter nodes in *data*.

4.2 Node Modelling Language (NODEML)

NODEML is a language that allows the abstraction of low-level details. More precisely, NODEML allows the definition of specific *nodes* that can be used to define a WSN. Once the nodes have been defined, they can be reused across different applications. Our node abstraction is based on the work that is described in [46]. More precisely, a node configuration can specify information such as operating system (e.g., TinyOS, Contiki, Mantis, LiteOS), **middleware** (such as TeenyLIME, MiLAN, RUNES [47]), **transportProtocol** (such as UDP and TCP), **macProtocol** (such as T-MAC, S-MAC, WiseMAC, SIFT [16]) and **routingProtocol** (such as SPIN, LEACH, GEAR [1]). From a structural perspective, in NODEML a WSN node contains one or more **energy sources** (e.g., batteries), a **microcontroller** (i.e., the component mainly devoted to computation and memory management), a set of **sensors**, a set of **actuators**, a set of **additional memories** representing external storage memories of the node, a set of **radio communication devices** to communicate with other nodes within the WSN, and a set of **power modes** in which the node can be at any given time.

As shown in Figure 5, the NODEML model developed for our hospital scenario is composed of two node configurations using TinyOS[5] as operating system, GEAR as routing protocol, and T-MAC as MAC protocol. The specified node configurations are detailed below:

[5] http://www.tinyos.net/

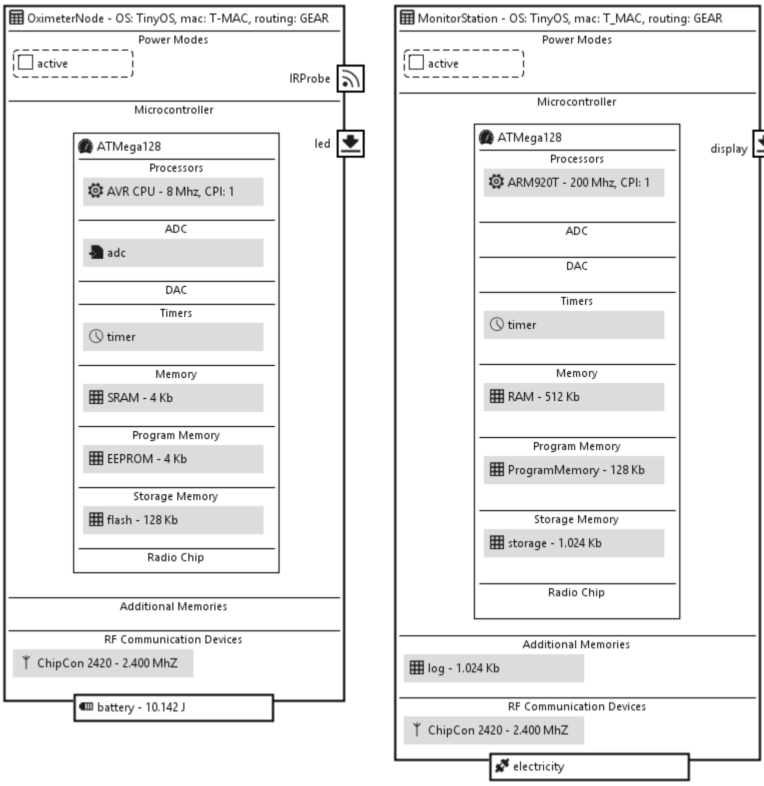

Fig. 5 Nodes configuration of the hospital scenario WSN

- *OximeterNode* is equipped with an *IRProbe* sensor for sensing the percentage of oxygen in the patient's blood and a led actuator for showing the current status of the node to the personnel of the hospital. This node is powered by two AA batteries with up to 18720 Joules and uses a Texas Instruments ChipCon 2420 RF transceiver. The micro-controller used is the low-power Atmel AVR ATmega128 equipped with an ADC for converting the analogue values read by the IRProbe sensor into their corresponding digital values. The oximeter node is always active (see the *active* power mode).
- *MonitorStation* has a single actuator device for graphically showing the values received by various oximeter nodes on a digital display. Similar to *OximeterNode*, it uses a Texas Instruments ChipCon 2420 RF transceiver and uses low-power Atmel AVR ATmega128 micro-controller. The monitoring station is always active (see the *active* power mode) and is powered by a classical electrical plug connected to the main electrical system of the hospital. Finally, it is equipped with an additional storage memory for storing a log of all the values received by the oximeter nodes over time.

4.3 Environment Modelling Language (ENVML)

The ENVML modelling language allows the designers to specify the physical environment in which the WSN nodes are deployed.

The **Environment** represents the overall area in the 2D space in which the WSN nodes are deployed. In ENVML an image can be associated to the specified environment, allowing environment designers to provide a more detailed view of the environment by means of external CAD software; in this case the proposed ENVML models can be seen a projection of these models which focusses on obstacles and inner areas only. Any kind of relevant **obstacle** can be placed in the environment. Each obstacle is characterized by the name of the *material* it is made of (e.g., concrete wall, wooden door, glass, etc.), and its *attenuation* coefficient. The shape of the obstacle is given by its *shell*: a sequence of **coordinates** representing the perimeter of the obstacle in the 2D space.

Figure 6 shows the ENVML model representing the physical environment of our hospital scenario. It is a rectangle with 16 and 13 meters of width and height, respectively and it contains three kinds of obstacles that are concrete walls dividing the whole environment into rooms and corridors, a main wooden door on the left, and a glass door for each patients room. Each obstacle is represented by a unique name, its attenuation coefficient and the coordinates of all the points of its perimeter.

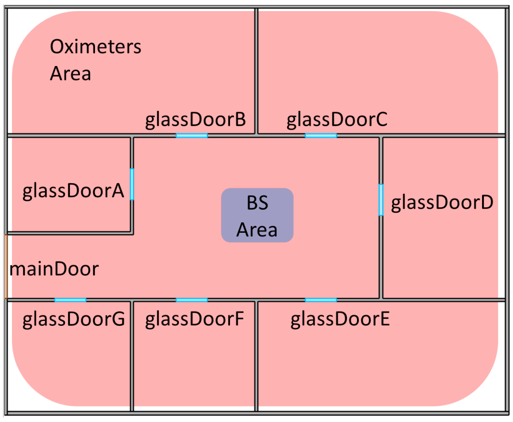

Fig. 6 Physical environment of the hospital scenario WSN

In ENVML an **area** identifies a portion of physical environment in which nodes of the same type can be distributed according to a distribution policy (defined in the DEPML modelling language, see Section 4.5). Similar to obstacles, the perimeter of the area is defined by means of its shell.

The physical environment of the hospital scenario contains two main deployment areas:

- *BSArea* is a square area at the center of the environment and will contain the central monitoring station.

- *OximetersArea* its perimeter is the same as the whole physical environment and will contain all the oximeter nodes, one for each patients' room.

It is important to note that the above mentioned solution is one of the possible deployment configurations; another solution could also consist in the creation of a single area for each oximeter, where each oximeter could be placed in the centre of the area. The aforementioned solutions share the same network topology.

4.4 Mapping Modelling Language (MAPML)

MAPML is the language for assigning software components to the corresponding hardware node configuration they will be executed on. A MAPML model semantically represents the classical notion of deployment of software components onto hardware resources [10]. The presence of an intermediate MAPML model between an SAML and a NODEML models helps in clearly separating the application layer from the lower levels of a WSN. So, architects can focus on the application from a functional point of view in SAML, while other engineers can focus on low-level aspects of the WSN in NODEML. This aspect is new in the Wireless Sensor Networks research area.

A MAPML model is made of a set of **node mappings**, each of them linking a node definition from the NODEML model and a component from the SAML model. The semantics of a node mapping is that the linked component in the SAML model will be physically deployed on the linked node in the NODEML model. A node mapping can contain a set of secondary links, each of them can be seen as a refinement of the node mapping. Secondary links are:

- **Sensor mapping**: it maps either a *sense* action or a *sensor interrupt* event in an SAML component to a *sensor* device in a NODEML node configuration. Fundamentally, this kind of link allows designers to specify to which physical sensor device does either a sense action or a sensor interrupt event refer to.
- **actuator mapping**: it maps either an *actuate* action or an *actuator interrupt* event in an SAML component to an *actuator* device in a NODEML node configuration. Conceptually, it is similar to sensor mapping, but it refers to actuators, rather than sensors.
- **Communication device mapping**: it maps an SAML message port of the component linked by the parent node mapping to a NODEML radio transceiver in the node configuration linked by the parent node mapping. It allows designers to physically map a software port to its corresponding physical radio transceiver.
- **mode mapping**: it maps an energy mode defined in an SAML component to its corresponding power mode in the linked NODEML node configuration. It allows designers to decouple the two concepts of mode we have in SAML and NODEML, and thus it opens for a more flexible definition of modes in the pure "software world", independently from the power modes that the WSN node has in the "physical world".

For what concerns our hospital scenario, the MAPML model (which links the SAML and NODEML model of Figure 4 and Figure 5) has the following form:

- *NodeMapping_oximeter* links the *Oximeter* component to the *OximeterNode* node;
  - *ModeMapping_active* links both the *normal* and *alarm* modes of the *Oximeter* component to the *active* power mode of the *OximeterNode* node. It is important to note that operating modes defined in SAML are pure logical modes, whereas power modes defined in NODEML actually depend on the hardware configuration of the node itself.
  - *SensorMapping_irProbe* links both the *SenseH(h)* and *SenseH2(h)* SAML sense actions to the hardware *IRProbe* sensor in the NODEML model.
  - *ActuatorMapping_led*, which is similar to *SensorMapping_irProbe*, links both the *turn(led.GREEN)* and *turn(led.RED)* SAML actions to the hardware *led* actuator in the NODEML model.
  - *CommunicationDeviceMapping_2420* links the *update* and *alarm* SAML message ports to the *ChipCon2420* RF transceiver defined in the NODEML model.
- *NodeMapping_monitor* links the *Monitor* component to the *MonitorStation* node;
  - *ModeMapping_active* links the *normal* mode of the *Monitor* component to the *active* power mode of the *MonitorStation* node.
  - *ActuatorMapping_display* links the *updateDisplay(data)* actuate SAML action to the hardware *display* actuator in the NODEML model.
  - *CommunicationDeviceMapping_2420* links the *update* and *alarm* SAML message ports of the *Monitor* component to the *ChipCon2420* RF transceiver defined in the NODEML model.

With such a configuration, we have a clear view of how various elements defined at the software architecture level interact with the hardware. For example, all the communication between the *Oximeter* and *Monitor* SAML components happen between different WSN nodes, whereas all the other actions defined in the control flow are executed locally to the component containing them. Also, the MAPML model establishes which hardware sensor and actuator equipments are actually used for performing the abstract sense and actuate actions defined in the SAML model. This level of flexibility is exactly the main goal of the A4WSN modelling approach.

The editor developed for the MAPML language is composed of three panels: left, centre and right. The left and right panels show the woven SAML and NODEML models, respectively, while the central panel represents various mappings of the MAPML model as a hierarchical tree. This solution allows us to provide a very clear and concise graphical editor for the MAPML model, which in some cases may have a very large number of interrelated mappings. Furthermore, we are aware that manually creating this large number of mappings can be a tedious and error-prone task for engineers; in this context, we are implementing a set of model-to-model transformations which are able to take as input an SAML model and a NODEML model, and then they are able to semi-automatically generate an initial MAPML model linking them; this operation is guided by matching strategies (e.g., name similarity via edit distance, structural similarity, etc.). In the MDE research field this practice is called *model matching* [15].

4.5 Deployment Modelling Language (DEPML)

DEPML is our language for virtually deploying WSN nodes into the physical environment. DEPML allows designers to consider each node configuration defined in a NODEML model and to *instantiate* it in a specific area within the physical environment defined in a ENVML model. A DEPML model contains a single type of link called **deployment link**, which links together a node configuration in NODEML and an area in ENVML. The semantics of the deployment link is that the linked node configuration is instantiated and virtually deployed in the linked area multiple times. This allow designers to focus on generic components and node types in SAML and NODEML, while in DEPML they can reason on the final deployment of the WSN. The number of nodes that are instantiated in the area is specified in the *numberOfNodes* attribute. Within a certain area each node configuration can be *distributed* in three different ways:

- *random*, each node is placed randomly within the area;
- *grid*, nodes are placed on a grid with a certain number of *rows* and *columns*;
- *custom*, each node is manually placed within the area. In this case, each **deployed node** is represented by its *name* (which must be unique within the area) and the coordinates of its *position*.

Also, **nodes name patterns** can be used by designers for declaring the textual pattern of the names of the nodes distributed within the area. They are used as a way to refer to the names used as targets of *send message* actions in SAML models.

For what concerns our hospital scenario, the DEPML model contains the following elements:

- *DeploymentLink_oximeter* links the *OximeterNode* NODEML node to the *OximetersArea* ENVML area. Since we want to specify that exactly one oximeter node must be deployed in each patient's room, we define a custom nodes distribution. Thus, we manually define the exact position of the deployed nodes by means of ten *deployed node* elements, each of them containing the coordinates of its position in the environment.
- *DeploymentLink_monitorStation* links the *MonitorStation* NODEML node to the *BSArea* ENVML area. In this case we specify that the number of deployed nodes is only one, with a random distribution within the area (we can do this because the area is a square with a side of 0.5 meters, which is exactly the size of the monitoring station node).

The presented DEPML models unveil the flexibility we achieved with the A4WSN approach. Indeed, if the hospital WSN application must be applied in a different hospital, the SAML, NODEML, and MAPML models can be reused as they are. The only models that must be adapted are: (i) the ENVML model for representing the new physical environment with its obstacles and (ii) the DEPML model for linking the original NODEML nodes to the new areas, possibly with different values for specifying the number of deployed nodes (e.g., twenty oximeter nodes instead of ten).

The DEPML modelling editor is analogous to the MAPML one: it is composed of three panels providing a tree-based representation of the NODEML, SAML and deployment links of DEPML, respectively.

4.6 Models correctness and Feasibility

All the proposed languages have been designed to provide a good trade-off between genericity, expressivity and accuracy in capturing the various facets of the WSN domain. To this respect, it is fundamental to allow designers to check whether their models are correct with respect to the semantics of the proposed languages. A4WSN provides two different mechanisms for checking the correctness of the developed models, namely: model conformance and a set of OCL constraints.

4.6.1 Conformance to metamodels

A4WSN allows designers to check whether a model adheres to the structural semantics of its corresponding language (e.g., SAML). A4WSN supports this feature by leveraging the well-known notion of **conformance** in Model-Driven Engineering; in other words, in A4WSN a model m adheres to the structural semantics of its corresponding language (e.g., SAML) if and only if m actually conforms to its metamodel (e.g., the SAML metamodel introduced in Section 4.1).

For example, if we refer to the SAML metamodel in Appendix A, we can see that the *StructuredDataDeclaration* metaclass has a *type* relationship to the *Expression* metaclass with multiplicity 1; this means that in every SAML model each declaration of a structured data must have one and only one type, defined as an expression. If an SAML model violates this constraint, then it is marked as invalid by A4WSN and the architect knows that this issue must be corrected. Also, if we consider the *value* relationship between the *DataDeclaration* and the *Expression* metaclasses, we can notice that its multiplicity is 0..1, meaning that in SAML models such a reference is optional, giving designers the freedom to either set a value to a data declaration (as an SAML expression) or not.

4.6.2 OCL constraints

In order to ensure a more precise semantics of the languages described in Section 4, we complemented them with a set of OCL[6] constraints. OCL is based on first-order predicate logic and it is a language to describe expressions and constraints predicating on models in an object-oriented fashion.

In A4WSN we use OCL constraints for predicating on the correctness and feasibility of the designed models. For example, the OCL constraint shown in Listing 1 is defined in the context of an SAML connection between components (line 1) and ensures that in SAML models each instance of *Connection* links together ports belonging to different components (line 3); when the constraint is violated the architect

[6] Object Constraint Language (OCL) specification: http://www.omg.org/spec/OCL/2.3.1

is informed about it via a dedicated error message (line 4). The A4WSN platform contains fourteen OCL constraints predicating on the various modelling languages of the platform. For example, another constraint in DEPML ensures that the coordinates of each manually positioned node must be within the boundaries of the area it is deployed in, and so on. For the sake of readability the description of such constraints are not discussed extensively in this article.

```
1 context Connection{
2   constraint sameComponentConnection {
3     check: (self.source.eContainer() = self.target.eContainer())
4     message: 'Source and target ports of the ' + self.source.name + '—
      ' + self.target.name + ' connection cannot belong to the same
      component'
5   }
6 }
```

Listing 1 Example of OCL constraint checking if an SAML connection links ports belonging to the same component

It is important to stress that our set of OCL constraints are defined in the context of all the A4WSN modelling languages. When considering the A4WSN auxiliary languages (i.e., MAPML and DEPML), our OCL constraints help architects and designers in actually evaluating the feasibility of either the software-hardware mapping (when considering MAPML models) or the virtual deployment of the nodes in the environment (when considering ENVML models). These OCL constraints are specially important since their checks crosscut multiple models conforming to different modelling languages; this is a non-trivial situation, where a manual analysis to identify and fix their violations could be very challenging for architects and designers. Listing 2 shows two OCL constraints performing two of those non-trivial cross-model checks.

```
context Sense{
  constraint senseActionNotMapped {
    check {
      // mapModel is a reference to a MAPML model
      for (m in mapModel.mappings.select(e|e.eClass().name='
    SensorMapping') {
        /* resolveLinkEnd() is a custom operation for obtaining a
        model element from a link end referring to it */
        if(m.senseAction.resolveLinkEnd() = self) {
          return true;
        }
      }
      return false;
    }
    message: 'The ' + self.name + ' SAML sense action is not mapped to
     any NODEML sensor'
  }
}

context SensorMapping{
  constraint sameComponentDifferentNode {
    check{
      var component = self.getComponent();
```

```
22        var node = self.getNode()
23        return not SensorMapping.allInstances.exists(p | (p.getComponent
      () = self.getComponent()) and (p.getNode() <> self.getNode()))
24      }
25      message: 'Two SAML sense actions belonging to the ' + self.
      getComponent() + ' component are mapped to two different NODEML
      nodes'
26    }
27  }
28
29  // returns the SAML component containing the mapped sense action
30  operation SensorMapping getComponent() : Component {
31    return self.senseAction.resolveLinkEnd().eContainer().eContainer();
32  }
33
34  // returns the NODEML node containing the mapped sensor
35  operation SensorMapping getNode() : Node {
36    return self.sensor.resolveLinkEnd().eContainer();
37  }
```

Listing 2 Examples of OCL contraints checking inter-model conditions between SAML and NODEML models

The *senseActionNotMapped* constraint is defined in the context of SAML sense actions (line 2) and checks among all MAPML sensor mappings (line 5) if there is one involving the current sense action (lines 8-12); an error message is shown to the architect if the current SAML sense action is not mapped to any NODEML sensor (line 14). Another non-trivial constraint is shown in lines 18-27 of Listing 2. This constraint is defined in the context of MAPML sensor mappings (line 18) and checks if there are SAML sense actions belonging to the same components, but at the same time they are mapped to more than one NODEML node (lines 21-24); this situation is erroneous in A4WSN because we assume that every SAML component is an atomic unit of deployment, i.e., an SAML component cannot be deployed to more than one NODEML node at the same time. As shown in lines 29-37, the OCL engine we use in the current implementation of A4WSN allows us to abstract complex operations on the models as auxiliary operations (see Appendix A for more detail). For example, the *getComponent()* operation is defined in the context of a MAPML sensor mapping, it identifies the linked SAML sense action (via another *resolveLinkEnd()* operation), and returns the SAML component containing the sense action by navigating upwards twice in the containment hierarchy of the SAML model. The *getNode()* operation performs a similar logic by identifying the NODEML node containing a NODEML sensor mapped by a specific MAPML sensor mapping.

If the need for more strict semantics of the proposed languages arises (for instance in order to define WSN applications with specific styles or special configurations), additional OCL constraints can be added to every element of the languages by extending the A4WSN platform with a suitable plugin. Please, refer to Section 5 for more details on this feature of the A4WSN platform.

4.7 Discussion

This section has presented a 3+2 modelling framework, that, by using three main modelling languages and two auxiliary ones supports the specification and analysis of WSNs. While a comparison with related work is provided in Section 7, the aim of this section is to briefly discuss why a new set of Domain-Specific Modelling Languages (DSMLs) is presented, instead of extending existing ones.

According to [44] *"Domain-specific languages (DSLs) are languages tailored to a specific application domain. They offer substantial gains in expressiveness and ease of use compared with general-purpose programming languages in their domain of application"*. While DSL and DSML are not synonyms of the same concept [9, 53], a number of advantages pointed in [44] still apply to DSML:

- domain-specific constructs defined for the domain of interest (WSN, in our specific case) are far more fine grained and specific of user-definable operators of existing modelling languages. More specifically, we could have expressed the SAML by profiling UML State Machines. However, this would have implied to force SAML to strictly follow the semantics of UML state machines and to introduce a number of other concepts by specialising UML constructs. Furthermore, the definition of the ENVML model would have required an under-specification of the 2D space.
- The use of DSMLs offers possibilities for analysis, verification and transformation that are far beyond what is supported by general-purpose languages. In our specific case, through the definition (and with an option to extend) the A4WSN modelling languages, we can run a multitude of domain-specific predictive analysis techniques (such as the PlaceLife plugin we developed to estimate the WSN lifetime - see Section 6).
- overall, DSMLs offer gains in reuse and maintenance. Accordingly, the A4WSN SAML, NODEML, and MAPML models are re-usable in different applications and applications domains.

When designing the modelling languages of A4WSN we aimed at representing the domain of WSNs in order to cover its most representative concepts and entities. We identified the set of concepts of the A4WSN modelling languages by working closely with industry partners and continuously performing informal interviews with engineers, developers, researchers and other involved stakeholders within WSN-based projects. So, it is important to stress the fact that with the proposed modelling languages we do not aim at addressing all the possible concerns in all possible situations about WSNs (e.g., dependability, sensing coverage, networking and communication, performance), specially because of the intrinsic multidisciplinary nature of the WSN problem space. Also, as already discussed in the literature about architecture description languages [43, 41, 17], having a comprehensive modelling language containing all the possible concepts related to a given domain may be unfeasible, or at least may lead to large and complex languages, which may be cognitively difficult to manage and maintain. The A4WSN platform targets the following concerns in the domain of WSN engineering: (i) separation of concerns, addressed via the multi-view modeling paradigm adopted in the modeling framework, (ii) reuse, addressed via the (independent) sharing of architecture, nodes, and environment models across projects and organizations, and (iii) model-based analysis, addressed via the A4WSN plugins system and its programming framework.

It is also important to note that the A4WSN modelling languages can be easily extended by means of generic and language-independent composition engines proposed in the literature. For example, in [17] we proposed a language composition engine that allows to extend architectural languages with domain-specific concerns, with new architectural views, with analysis constructs or with methodology and process concepts, depending on the system's stakeholder concerns. In this case, the needed additional concepts may live in dedicated plugins of the A4WSN platform, and can be used by the WSN engineers when needed.

5 The Programming Framework

As introduced in the beginning of Section 3, the A4WSN platform is composed of two main parts that are a modelling environment to allow architects to model WSN applications and a programming framework devoted to code generation and analysis of WSN application models. The motivation for performing code generation and analysis of WSN application models are well understood both in academia and in practice [55,36]. Basically, code generation helps in reducing the cost of developing a WSN application since the developers can automatically obtain an executable application from the model by applying some specific transformations. Also, performing analysis is fundamental while developing a WSN application due to the intrinsic complexity of the WSN domain. For example, if we consider typical aspects in WSN development such as nodes connectivity, real-time communication, energy consumption, performance, security, etc., it is extremely difficult and demands a lot of effort to ensure that a developed WSN is correct with respect to those aspects. Moreover, analysis engines can also be used to reason on the WSN configuration in order to find reasonable trade-offs in terms of network topology, employed protocols, etc. for a specific task.

In this section we present the *generic and extensible* programming framework of A4WSN. It is tailored to support the development of code generation and analysis engines against WSN application models conforming to the modelling languages described in Section 4.

Our programming framework offers a generic workbench and a set of extension points for supporting the development and integration of third-party code generation and analysis engines. More specifically, through its components, it enables the storage of WSN models, supports the merging of linked models, validates A4WSN models, provides error/warning/information messages to the user, defines a UI manager to make plugins interacting, provides facilities for managing code generation and analysis engines.

Third-party engines are realised as plugins extending the A4WSN generic workbench. It knows at run-time which plugins are available and automatically provides to the user the available target implementation languages and analysis techniques.

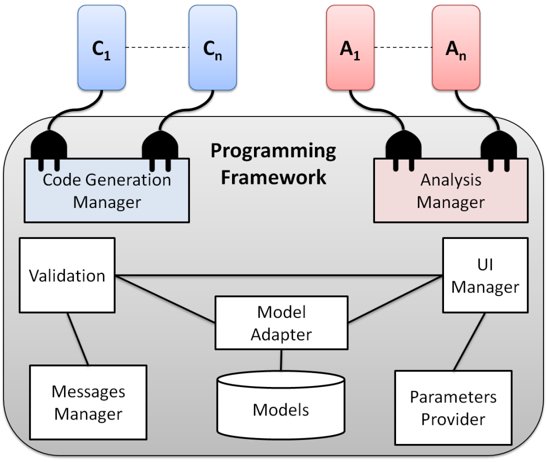

Fig. 7 The A4WSN programming framework

Figure 7 shows an overview of the A4WSN programming framework. All the boxes within the programming framework represent the various components of the generic programming workbench, whereas the $C_1..C_n$ and $A_1..A_n$ boxes represent third-party code generation and analysis plugins, respectively. Third-party plugins extend the *Code Generation Manager* and *Analysis Manager* components which provide the needed extension points and they communicate with all the other components of the programming framework (for the sake of clarity we do not show those connectors in the figure). In the following we will briefly introduce the facilities and duties of the various components. A detailed description of each component is presented in Appendix B, while the overview of their implementation details is provided in Appendix C.

- Models: it is a repository that stores all the WSN models developed by architects and designers;
- Model Adapter: it abstracts the nature of the models repository to the other components of the A4WSN programming framework, so to avoid interoperability issues;
- Validation: it executes validation operations, such as model to metamodel conformance, and OCL constrains satisfaction;
- Messages Manager: it graphically shows three kind of informative messages to users, which are *error, warning and information*;
- UI Manager: it provides the facilities to interact with the user interface of the A4WSN platform;
- Parameter Provider: it manages the additional parameters required by a code generation or analysis plugin;
- Code Generation Manager: it provides the services required to manage code generation engines, such as extension checks, list of plugins, plugins load, validation triggering;

- Analysis Manager: it is analogous to the Code Generation Manager, but designed for analysis plugins;
- Extension Points: it provides services and rules to connect other components to the A4WSN framework.

6 PlaceLife: an A4WSN plug-in

In order to validate the expressivity of the A4WSN modelling languages and to exercise the provided extension points, we developed an analysis plug-in called PlaceLife. PlaceLife takes advantage of the three modelling views (namely, SAML, NODEML and ENVML) in order to provide an estimate of the WSN lifetime. All modelling views are analysed, combined and translated into low level simulation scripts that can be executed to estimate the WSN lifetime. This translation has been useful to verify that our models have an appropriate level of detail for simulation purposes. In order to produce a realistic simulation the following is desirable:

- **abstraction:** the models abstract all the details needed to generate scripts that can run in various well-accepted simulators such as Opnet and OMNET++;
- **fine-grain simulation:** the details should allow fine-grain simulations that combine different information such as physical environment, hardware and various layers of OSI.

We verify abstraction by considering all OSI layers and for each layer the information required by well-established simulation tools. We show that in most of the cases A4WSN models abstract the information but missing ones can be easily added via a specific plug-in. More precisely we keep the core modelling languages (i.e., SAML, NODEML, ENVML) as clean and minimal as possible, without polluting them with analysis- or code generation-specific constructs; at the same time engineers can add their own analysis-specific models and concepts via dedicated plugins in order to streamline the analyses that they need to perform. For instance in the healthcare case study A4WSN models the application behaviour (e.g., sampling rate and event notification policy) while PlaceLife can provide input models to Castalia. This is shown from Section 6.1 to Section 6.3.

Fine-grain simulations are easily obtained thanks to the reuse and the weaving of multiple models into a single one. Models such as NODEML or ENVML that contain low level information (e.g., hardware and path loss) can be created once and reused multiple times with different application models. This has been validated in Section 6.6 by means of a home automation application. Technical details such as the effects of the path loss and the hardware which require theories of telecommunication are specified in pre built PlaceLife models. Technical details are complemented with the application model (i.e, SAML) and the physical environment (i.e., ENVML). These models are transformed into various complex simulation scripts. In Section 6.5 we describe the PlaceLife implementation and the simulation tool used as a target language for simulation script generation (that is, Castalia). In section 6.6 we compare the simulation results obtained with a basic Castalia simulation with a PlaceLife simulation based on pre-built hardware and path loss models, applied to the fire alarm and automatic heating application. Numerical results are also presented to show the effects of realistic simulation scenario, where environmental factors are taken into account. The former has the default ideal free space model for the path loss while the latter considers pre-built PlaceLife models that consider the real environment that is made of physical objects. We see that not considering the real environment may cause overestimation of the lifetime which is particularly undesirable.

6.1 Application layer

Information at application layer should include the structure and behaviour of the WSN. For instance this includes type of components, number of instances and their interaction. This information is useful to derive relevant data such as the sensing rate, messages sent over the network and the type of communication (broadcast, multicast and point-to point). This data clearly affects the energy consumption. Beside the structure and the behaviour of the WSN, useful application layer information can be the used aggregation protocol[7] [31,56] (if any), the type of operating system, the type of middleware (if any) and so on.

The modelling languages of A4WSN provide ways to define all the aforementioned application layer information. The SAML view contains structure and behaviour of the WSN application. For instance this includes the type of components, their interaction, the sensing and transmission activities of a node and the type of transmission. This information is complemented by the NODEML view that specifies, among the other information, the type of operating system and the middleware used. In PlaceLife we use the ENVML and DEPML models in order to have data about the number of nodes within the WSN and their deployment position in the environment. Application layer information is translated into low level scripts. More precisely, structure and behaviour are translated into simulation scripts. These scripts are combined with components from the simulation library (such as sensing components and middleware) in order to obtain the entire application layer configuration of the simulation. While PlaceLife provides the implementation of some libraries, unimplemented ones such as unknown sensors or unsupported middleware need to be specified by the user.

6.2 Networking and data link layers

Information at networking layer should specify the routing protocol. While routing can be performed by using a multi-hop solution, clustering approaches are very effective in order to improve the energy efficiency of the WSNs. This is why the NODEML can specify either multi-hop routing protocols (e.g., AODV) or some clustering approach (e.g., LEACH). A static routing can also be defined by explicitly specifying the connection among nodes. Routing that are not supported by A4WSN must be implemented by using some simulation script language.

[7] Aggregation and fusion aims at removing redundant data and transmitting concise information.

Information at data link layer should include the medium access method (MAC) that is used. Access methods can be summarised into two main categories: contention based method (e.g., CSMA/CA) and channel partitioning (e.g., TDMA). The NODEML includes a wide range of possibilities for the MAC protocol selection. This includes CSMA, T-MAC and S-MAC [74, 13].

6.3 Physical layer and hardware

Physical layer information should support the definition of an energy consumption model for realistic estimate of the WSN lifetime. An advanced energy consumption model should consider the path loss, the modulation scheme, the hardware that is used, the coding scheme and so on. While the modulation scheme, the hardware and the coding scheme are specified in the NODEML model, the path loss, as we show in the next section, has been defined according to the environment and its obstacles. NODEML, ENVML and path loss definitions are used to generate low level settings and scripts that can provide a fine estimate of the energy required to transmit a bit over the physical channel.

6.3.1 The path loss

In sensor networks, path loss can play a crucial role since neglecting the path loss may cause overestimation of WSN lifetime. The optimistic evaluation of resources is particularly dangerous for WSNs since the resources come with significant restrictions especially in terms of energy. The path loss is reduction in transmitted signal strength as a function of distance, which determines how far apart two sensor devices can be and have reliable communication between the devices [52]. The core of signal coverage calculations for any environment is a path loss model, which relates the loss of signal strength to the distance between two terminals and the operating frequency.

Indoor radio propagation is dominated by the same mechanisms as outdoor propagation: reflection, scattering, diffraction, refraction, absorption and depolarization. However, conditions are much more variable. The indoor environment differs widely due to the increased number of obstacles, layout of rooms, presence of multiple walls and floors, windows and open spaces. Altogether these factors have a significant impact on path loss in an indoor environment. Due to the irregularity in the position of obstacles and layout of the rooms, the channel varies significantly with the environment making the indoor propagation modelling relatively inconsistent and challenging especially for modelling. The propagation and path loss models are usually based on empirical studies on the system considered.

Accurate modeling of the actual environment is very complex as the communication systems operate in complex propagation environments. In practice, most of the simulation studies make use of the empirical models that have been developed based on empirical measurements over a given distance in a given operational frequency range and a particular environment [57]. Some of the most common empirical models include Okumura Model, Hata Model, COST 231-Walfish-Ikegami Model, Erceg Model, ITU Indoor Path Loss Model, Log-Distance Path Loss Model etc [57, 64].

Table 1 Partition dependent losses for 2.4 Ghz

Attenuating Material	Signal attenuation in dB
Wood	2
Metal frame, glass wall into building	6
Office wall	6
Metal door in office wall	6
Cinder wall	4
Metal door in brick wall	12.4
Brick wall next to metal door	3

When considering an indoor propagation environment for path loss, the material used for walls and floors, the layout of rooms, windows and open areas, location and materials obstructing etc. should be taken into account, as all of these factors have a substantial impact on the path loss in an indoor environment. The complexity of signal propagation in the indoor environment makes it difficult to obtain a single model that illustrates path loss across a wide range of environments. The following is a commonly used simplified model for path loss as a function of distance [24].

$$P_r\ (dBm) = P_t\ (dBm) + K(dB) - 10\gamma\ log_{10}\left(\frac{d}{d_0}\right) \tag{1}$$

where P_r is the received signal strength and P_t is the transmitted signal strength; K is the path loss factor (it depends on antenna characteristics and the average channel attenuation), γ is the path loss exponent, d_0 is the reference distance for the antenna far field, and is typically assumed to be 1-10m for indoor scenarios and 10-100m for outdoor scenarios. The path loss factor K can be calculated as:

$$K\ (dB)\ =\ 20\ log_{10}\frac{\lambda}{4\pi d_0} \tag{2}$$

The value of λ depends on the propagation environment. This path loss model, together with the ENVML physical environmental model, is used to define the path loss between any two nodes. Please note that existing simulation packages, and modelling architectures do not consider the effects of path loss to best of our knowledge. We fix the value of γ at 2 for free space and introduce the losses for each partition (obstacle) that is encountered by a straight line connecting the receiver and the transmitter. Please refer to Table 1 for the decibel loss values measured for different type of partitions, at 2.4 GHz [52]. In order to add the effects of obstacles between the transmitter and the receiver, we add the fixed path losses per existing obstacles to the free space path loss.

There is no doubt that the physical layer has a fundamental role when energy consumption is considered. Researchers are currently investigating various modulations and coding techniques. Choosing a model for energy consumption can also be complicated. Different studies and simulation tools [27] [7] [70] consider different models for energy consumption.

6.4 Analytical model

In this section the analytical framework for calculation of the lifetime of nodes is presented. The analytical model presented is in turn used to verify the simulation results. The analytical framework consider the characteristics of the transmission process which affects the lifetime of a node. Without loss of generality, the lifetime L of a node n can be expressed as:

$$L_n = \frac{E_{tot}}{E_{pr} \times R_r + E_{pt} \times R_t} \tag{3}$$

where L_{node} is the lifetime of the nodes, E_{tot} is the total energy in joules available for the node considered (e.g. initial energy for two AA battery is 18720 joules), E_{pr} and E_{pt} are the energy spent to receive and transmit a single packet, and R_r and R_t are the average number of packets received and sent per second respectively.

For the analytical framework introduced in this paper the energy consumption model described in[7] is combined with the effective number of transmissions including the retransmissions caused by obstacles. This model is selected since it includes various factors such as distance, attenuation due to obstacles, modulation, and hardware. The energy consumption of a node n is affected by the following three terms:

- E_{ct}: the transmitter circuit energy;
- E_{cr}: the receiver circuit energy;
- E_t: the transmission energy.

The calculation of the transmission energy E_t is based on the following expression:

$$E_t = \frac{L \times M \times N_f \times N_0}{\gamma \times G} \times f_{\tau,\Im}(B) \tag{4}$$

where L is the path-loss (see [35] for details), M is the link safety margin, N_f is the receiver noise figure, N_0 is the ambient noise power spectral density, γ is the power amplifier efficiency, G is the combined gain of the transmit and receive antennas, $f_{\tau,\Im}(B)$ is the required signal-to-noise ratio per bit corresponding to transmission technique τ, fading characteristics $\Im$ and target bit error rate B.

The energy spent for receiving a packet can be calculated as follows:

$$E_{pr} = E_{cr} \times s \tag{5}$$

where s is the packet size.

6.5 PlaceLife implementation

PlaceLife generates Castalia and OMNET++ [50] simulation scripts. Castalia is a WSN simulator based on the OMNeT++ platform. It is mainly used for initial testing of protocols and/or algorithms with a realistic node behaviour, wireless channel and radio models. The OMNeT++ platform is an extensible, modular, component-based C++ simulation library and framework, primarily for building network simulators.

Castalia is used in order to simulate the radio channel, the MAC protocol and the network protocol. The application behaviour is needed to derive application level simulation parameters. The environment and the path loss models allow the calculation of the path loss. In fact, while Castalia assumes that the user provides path loss related parameters in a complex path loss matrix, PlaceLife presents an abstract view of the environment where the path loss is derived based on the characteristics of the environment specified in the ENVML model. OMNET++ is used for additional simulation components such as the sensing devices and the middleware library.

6.6 PlaceLife applied to the home automation system: Numerical Results and Discussions

In order to show the effectiveness of the architectural approach and the PlaceLife plugin, in this section (i) we consider a case study about a home automation system, and (ii) we present numerical results of its simulation. The numerical results also show the effects of realistic simulation scenarios, where environmental factors are taken into account.

Monitoring and automatic control of building environment is a case study considered quite often [26], [22]. Home automation can include the following functionalities: (i) heating, ventilation, and air conditioning (HVAC) systems; (ii) emergency control systems (fire alarms); (iii) centralised lighting control; and (iv) other systems, to provide comfort, energy efficiency and security. In order to validate our approach we consider the fire alarm system and the automatic heating application. A CC2420 chip, compatible with 802.15.4, is used to provide wireless communication, operating at 2.4 GHz and providing a maximum data rate of 250 kbps. The transmission output power with which the radio transmits the packets is 0dBm. It employs Direct Sequence Spread Spectrum (DSSS) modulation in combination with Offset - Quadrature Phase Shift Keying (O-QPSK) modulation. Each node is powered by two AA batteries with up to 18720 Joules and uses a Texas Instruments ChipCon 2420 RF transceiver. Low-power Atmel AVR ATmega128 equipped with an ADC is used

Table 2 Selected values

link safety margin	M=10
receiver noise figure	N_f=5
ambient noise power spectral density	$N_0 = -204$dBJ
power amplifier efficiency	γ=0.35
combined gain of the transmit and receive antennas	G = 1
required signal-to-noise ratio per bit τ=transmission technique $\Im$= fading characteristics and B=target bit error rate	$f_{\tau,\Im}(B)$ = 15dB
circuitry	$E_{ct} = E_{cr} = 1\mu J$

as the micro controller. The fire alarm system is composed of temperature sensors, smoke detectors and sprinkler actuators. In our fire alarm implementation we assume that all the temperature sensors monitor the temperature at regular intervals Δt_1. When a temperature sensor reads a value that exceeds a specified threshold T and a smoke sensor detects smoke all the sprinklers are activated. The value Δt_1 and the threshold T are assumed to be 30 seconds and 50 celsius degree, respectively.

The automatic heating application is composed of different temperature sensors, a base station, and various heaters. In our automatic heating application the temperature sensors send readings at regular intervals Δt_2 to the base station directly (no routing protocol is employed as the sensors communicate directly to the base station). This is placed at the center forming a star topology. The base station averages the readings and decides whether or not the central heating system should be on. More specifically the base station works in the following way:

- if the heating is turned on and the average temperature is greater than the maximum temperature T_{max}, the central heating system turns off.
- if the average temperature is less than the minimum temperature T_{min}, the central heating system turns on.

The value Δt_2 is set to be 30 seconds while $T_{min} = T_{max} = 22$ Celsius degree. We assume the fire alarm system and the automatic heating application are deployed in a building composed of three floors. Each floor has the same floor plan that is shown in Figure 8. It is important to note that base stations interference is negligible since base stations have no energy limitations and they do not use different channels.

Figure 8 represents the floor plan of an apartment, containing the temperature and smoke detector nodes. For the sake of representation, we use numbers to represent sensor nodes monitoring temperature and smoke, and we do not present the various models representing the WSN, rather we directly describe the main results of the execution of the automatically generated simulation scripts. Nodes 1, 2 represent the temperature and smoke detector nodes respectively in the bathroom area. Nodes 3,4 respectively represent the temperature and smoke detector nodes in the pantry. Nodes 5, 6 represent the temperature and smoke detector nodes respectively in the kitchen, nodes 7,8 represent temperature and smoke detectors respectively in the storage area while nodes 9, 10 represent the nodes from the outer hallway and stairs to the lobby. All these temperature nodes in these areas sense and send to the base station located close to the pantry.

In the larger bedroom, nodes 11, 12 represent the temperature and smoke detectors nodes respectively, nodes 15, 16 represent temperature and smoke detector nodes in the living room, while 17, 18 represent temperature and smoke detector nodes in the smaller bedroom. In the closet attached to the smaller bedroom, nodes 19, 20 represent temperature and smoke detector nodes respectively. Nodes 21 and 22 respectively represent temperature and smoke detector nodes in the lobby. Nodes 13, 14 are temperature and smoke detector nodes respectively, located close to the base station in the living room. All the temperature nodes in these areas sense and send their data to the base station in the living room. The base stations are connected to each other using peer-to-peer connection. Coloured representation of the signal strength degradation due to obstacles can be seen in the Figure 8. Coloured representation is used to

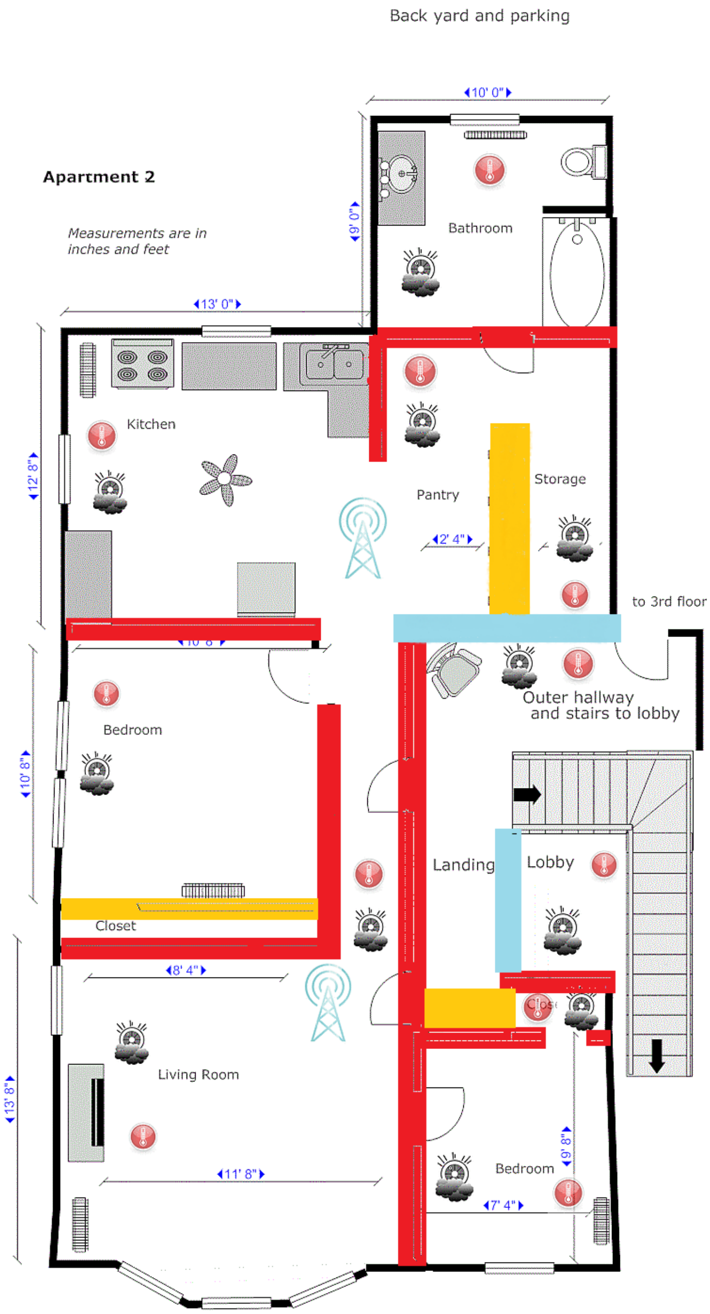

Fig. 8 Home automation - case study

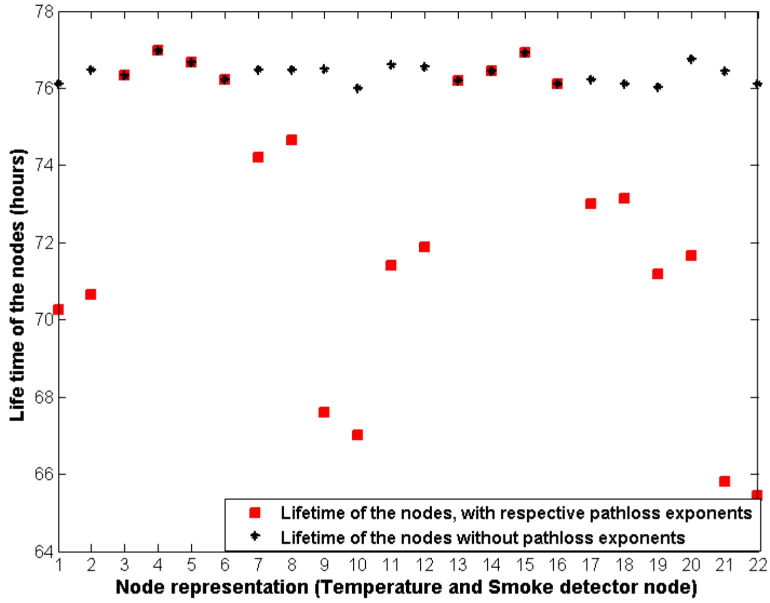

Fig. 9 Life time of the nodes

clearly show the effect of signal strength due to obstacles in the home environment. Wooden obstacles are represented in yellow, glass obstacles are represented in blue, and concrete walls are represented in red; the areas not affected by path loss due to obstacles are not coloured.

Figure 9 shows the energy consumption of each node in one of the floors of the building for free space environment and when the path loss due to obstacles (mainly due to partitions) is introduced. It is evident that ignoring the effect of path loss would be an optimistic assumption when energy consumed by each node is considered. The obstacles considered are mainly the wall partitions used for indoor segmentation. The results clearly show that avoiding path loss would cause overestimation of the WSN lifetime. More precisely, the lifetime of the nodes 1 and 2 deployed in the bathroom area is about 76 hours with no path-loss as compared to 70.5 when the exponent due to the brick wall separating the bathroom and the pantry are considered. Similarly, the lifetime of the nodes 21 and 22 is about 65.5 hours when the attenuation due to the glass partition in the lobby area and also the brick wall separating the landing area and the living room, as compared to 76 hours ignoring the effects of path loss. It can also be observed that the nodes 3, 4, 5, 6, 13, 14, 15, 16 are not affected by path-loss as they are not enclosed by walls or any obstacles. Hence, their lifetime is roughly about 76.5 hours.

It is evident that ignoring the effect of path loss would be an optimistic assumption when energy consumed by each node is considered. Results presented in Figure 9 are particularly important to show the usefulness of a detailed and a realistic modelling tool. Our PlaceLife plug-in allows engineers to consider the nature of the obstacles of the environment in details, thus providing a more realistic performance measurement. Our PlaceLife plugin allows engineers to consider the nature of the obstacles of the environment in details, thus providing a more realistic performance measurement. While various components of PlaceLife are employed, the design of the simulation does not get complicated since the architecture presented is user friendly. Please note that the multi-view architectural approach allows the user to isolate the physical environment an incorporate various factors such as path loss, shadowing etc.

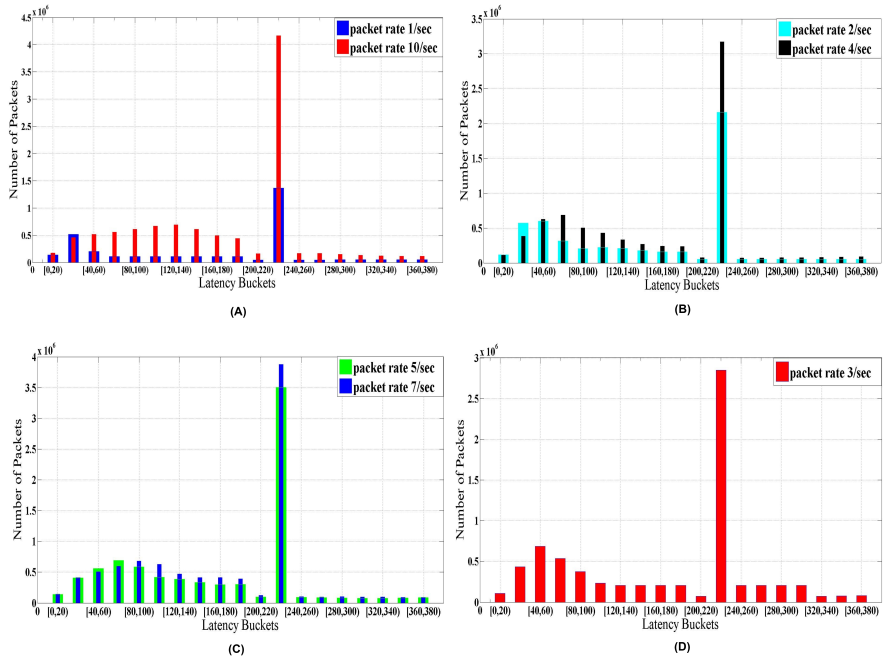

Fig. 10 Delay incurred at the base station

The simulation tool employed allows us to consider other measurements in addition to the lifetime of the WSN nodes. Various performance measures such as response time (latency), the number of dropped packets etc. can be analysed in detail. Figure 10 shows the latency of the packets received by the monitoring station located in the living room. The results show that most of the packets have a latency interval of 230 ms. As the packet rate increases, the number of packets within the same latency interval also increases. The figure also demonstrates the flexibility of the considered system in terms of performance, availability, and energy-related measures.

7 Related Work

In order to simplify the design and configuration of the WSN at large, and abstract from technical low-level details, a number of MDE approaches or of modelling notations for WSN engineering have been proposed. Those approaches are used to specify a WSN at different levels of abstraction (hardware, application, communication protocols, etc.) with the recurrent goals of code generation, communication overhead analysis, and energy consumption.

The rest of this section is structured so to cover three related research areas: i) frameworks for the engineering of WSNs (or related domains), ii) domain-specific modelling languages for WSN, iii) other modelling and analysis approaches for engineering WSNs, and iv) surveys related to the modelling and analysis of WSNs.

Frameworks for Engineering WSNs (or related domains): Engineering frameworks strongly related to A4WSN have been presented in [6,65,54].

In Reference [6] the authors propose DiaSuite, a tool suite proposed for the design, analysis, and deployment of Sense/Compute/Control applications. The DiaSuite domain specific design language supports the modelling of a taxonomy layer and an application design layer. Those models are successively used to generate a dedicated Java programming framework (to guide and support programmers to implement the various parts of the software system), for simulation purposes, and for deploying the application on a specific execution platform. When compared with A4WSN, DiaSuite has similar goals (modelling for analysis a code generation), but covers a different domain. As a result, the modelling languages are extremely different, and are manipulated (for analysis and code generation) in different ways.

In [65] a set of modelling languages is the starting point for code generation and performance (with energy consumption) analysis. Those languages are based on concepts such as sampling task, aggregation task, network communication tasks, etc. and they are the starting point of a model-driven process to enable a low-cost prototyping and optimisation of WSN applications. In [49], a framework for modelling, simulation, and code generation of WSNs is presented. The framework is based on Simulink, Stateflow and Embedded Coder, and allows engineers to simulate and automatically generate code with energy as one of the main issues.

In Reference [54] a multi-stage model-driven approach for IoT applications development has been proposed. Such an approach takes into explicit consideration the existence of five different types of IoT stakeholders, and according to their needs, propose five different modelling languages. Those models are successively used for code-generation and task-mapping techniques. Similarly to DiaSuite [6], while sharing the same goals of A4WSN, the framework in [54] covers a different (still, related) domain.

Domain-specific modelling languages for WSN: many approaches propose to use DSMLs for representing WSNs from different viewpoints. For example, in [71] the proposed modelling language contains concepts such as node group, region, resource, wireless link; whereas, in [19] authors propose a set of languages spanning from application-level actions (e.g., sense, send message, store data) to hardware specifications (e.g., processor, sensing devices, radio transceivers), and so on. In [69] the authors propose Verisensor, a DSML based on concepts such as system, node class, application etc., with the possibility to automatically translate models towards a formal language for checking the lifetime of the WSN and its correct behaviour.

In [14], the authors propose the LWiSSy domain specific language for wireless sensor and actuator network systems. The LWiSSy metamodel comprises three views: structural behavioural, and optimisation. Those three views are described in details, and successively evaluated through a controlled experiment.

Other approaches, such as those proposed in [48] and [21], are based on *generic modelling languages*. They mainly use extensions of UML and Simulink for representing a WSN.

In order to better understand how MDE has been used for designing and analysing wireless sensor networks, [39] surveys and classifies state-of-the-art MDE approaches for engineering WSNs.

Other modelling and analysis approaches for engineering WSNs: describing a network from a *structural* point of view is very straightforward and easy to reason on (just think about the component-based representation in Omnet++[8], one of the most popular network simulators). Also, an approach based on DDS (i.e., the data-centric middleware standard introduced by OMG) is presented in [4]; the authors proposed four types of modelling languages (namely for data types, data space, node structure, and node conguration) and use them as input for a set of optimisation and transformation steps, eventually delivering deployable application code as output.

Also, in some cases (e.g., when capabilities such as fault tolerance and security analysis are needed) the structure of WSNs may not be enough, and thus describing the *behaviour* of the WSN is fundamental. In [25], the authors address energy-aware system design of Wireless Sensor Networks (WSNs). Energy mode signalling and energy scheduling of nodes within a WSN are represented as SDL models, and then analysed.

Rodrigues et al. in [58] proposes an MDA process where application domain experts model the Platform Independent Model (PIM) of a WSN application. Such a PIM is successively transformed into a Platform Specific Model (PSM) and refined by a network expert. Class and Activity diagrams are used to specify the WSN application at the PIM level, while Component and Finite State diagrams are used at the PSM level.

An approach for formal modelling and analysis of WSN in Real-Time Maude is presented in [51]. In [63] Samper et al. propose the GLONEMO formal model for the analysis of ad-hoc sensor networks.

For what concerns the *physical environment* of a WSN, the majority of approaches in the literature does not allow designers to specify the *physical deployment* of the WSN nodes. Among those that support (in some form) this feature, there is great variability. There are some approach which support an explicit definition of the physical environment (e.g., in [19] the tool allows engineers to model real-world dimensions, obstacles with attenuation coefficients, etc.); others allow designers to define physical quantities (e.g., in [5] engineers can define models of the evolution of each physical quantity in a given scenario), and so on. However, all these approaches do not provide any intuitive and abstract means to easily define the deployment environment of the

[8] http://www.omnetpp.org/

WSN. A recent study [40] has investigated how WSN engineers currently specify the physical environment and how they would like to do it.

Surveys related to the modelling and analysis of WSNs: A survey on system models in WSNs has been conducted in [68]: there the authors identify several dimensions to be used to classify model (types) used to specify networked computing systems (from models of signal propagation, to models of the application). Existing models are then organized into a taxonomy. In [34] the authors survey 9 WSN modelling techniques. Through this study, they show how each technique models different parts of the system. The models here analyzed are extensions to existing notations, such as SDL, Promela, UML, and others.

Final Remarks: A4WSN shares with some of the related approaches above the wish to provide a *clear separation of concerns* between different modelling views, to enhance *reuse*, to *abstract* from low level details, and to support *early analysis* of WSN applications. What distinguishes A4WSN from other related work are i) the modelling languages that have been selected for modelling WSN applications, including an explicit graphical modelling of the application physical environment, ii) the definition of models dedicated to the weaving of the three main modelling languages, iii) the existence of an extensible programming framework that enables third-party researchers and developers to reuse the A4WSN modelling environment and programming framework when developing new analysis and code generation engines. In this context, third-party researchers can focus exclusively on solving their peculiar issues, while spending minimal effort and implementation time on realizing the facilities already provided by A4WSN out of the box. iv) The maturity of A4WSN with respect to other approaches that, while sharing some of our desires, seem to still implement only a subset of them.

8 Conclusion and Future Work

In this paper a modelling platform supported by a dedicated programming framework for the model-driven engineering of wireless sensor networks. The modelling viewpoints and conceptual elements have been carefully designed in collaboration with colleagues from various domains, such as software engineering, wireless sensor networks, and telecommunications. The programming framework functioning has been tested by realizing a plugin devoted to energy-related simulation of WSNs.

The modelling and programming framework presented in this paper represent the (starting but mandatory) foundation for a series of goals we are willing to achieve in the mid-term.

Firstly, we plan to have the framework used by practitioners involved in the development of WSNs. We wish to record and analyze their usage patterns and collect their feedback for further improving our platform. At the time of writing, the framework is being used by master students to model and analyze course projects, and it is currently used in situational awareness projects handled by one of the co-authors.

Secondly, we are aware that it might be necessary to extend the modelling languages to provide additional concepts for supporting new analysis or code generation engines. For example, we are working on providing new SAML data structures (either primitive or structured), new attributes for better specifying nodes in the NODEML modelling language, and on the extension of the purposefully simple ENVML modelling language (e.g., by adding multi-floor support for indoor deployments, by supporting the specification of properties specific to outdoor setups, etc.). In this context, introducing changes at the metamodel level might have a strong impact on the already developed plugins (model editors, model transformations, etc.). This problem is called metamodel co-evolution management and it is well-known in the MDE research field [11,60]. If we look at this problem from a different perspective, similarly to what we proposed in a previous work on architectural languages interoperability [62], a possible solution could be to provide a systematically defined extension process for our modelling languages. According to this extension process, languages extensions are organised into a hierarchy obtained by systematically extending a root modelling language. Under this perspective, we plan to build on (and adapt, if needed) metamodel co-evolution techniques [61,32] in order to tackle this problem.

Thirdly, we would like to realise an analysis plug-in that, while getting in input a series of environmental configurations options, can tell us which configuration can increase the network lifetime (so far, PlaceLife can evaluate the expected lifetime of a given configuration, but is quite impractical to analyse comparatively alternative solutions). We plan to use genetic algorithms and search-based approaches to achieve such a goal.

Finally, we are working on a WSN performance analysis plugin that allows engineers to run a trade-off analysis between energy consumption and performance indices like sensor nodes throughput, reliability and network latency.

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Appendix A: The metamodels of the A4WSN modeling languages

In this appendix we show the metamodels of the A4WSN modeling languages. For the sake of brevity, we do not describe each element of the languages, the details are presented in the a dedicated technical report available online [38].

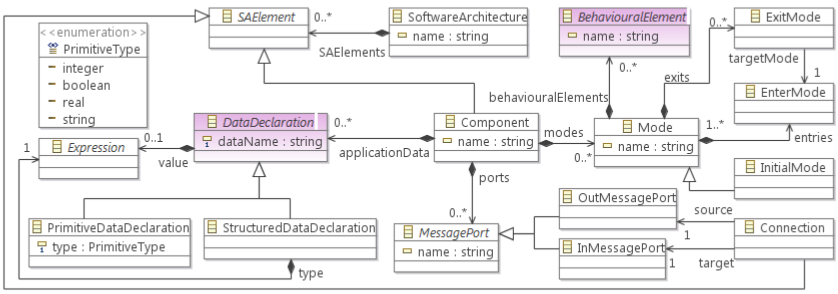

Fig. 11 SAML Metamodel: structural concepts (external metaclasses in pink)

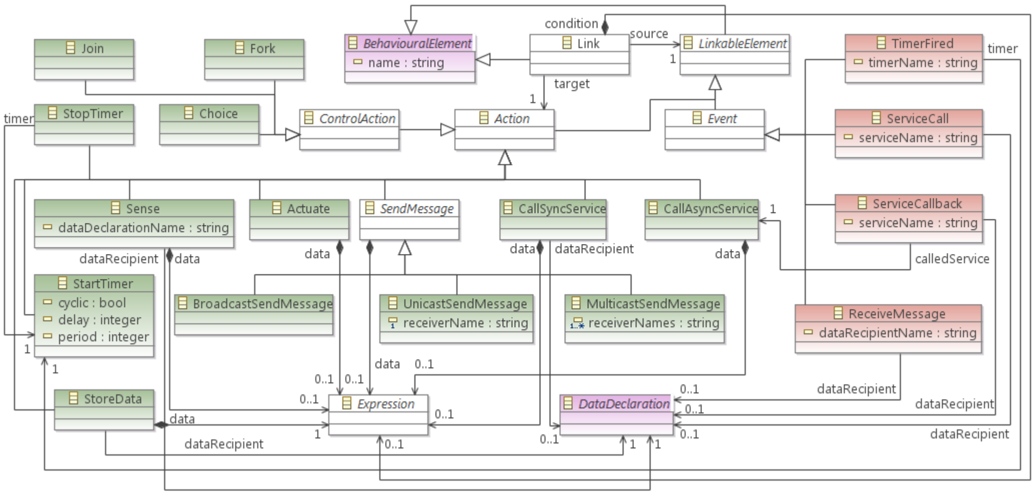

Fig. 12 SAML Metamodel: behavioural concepts (actions in green, events in red)

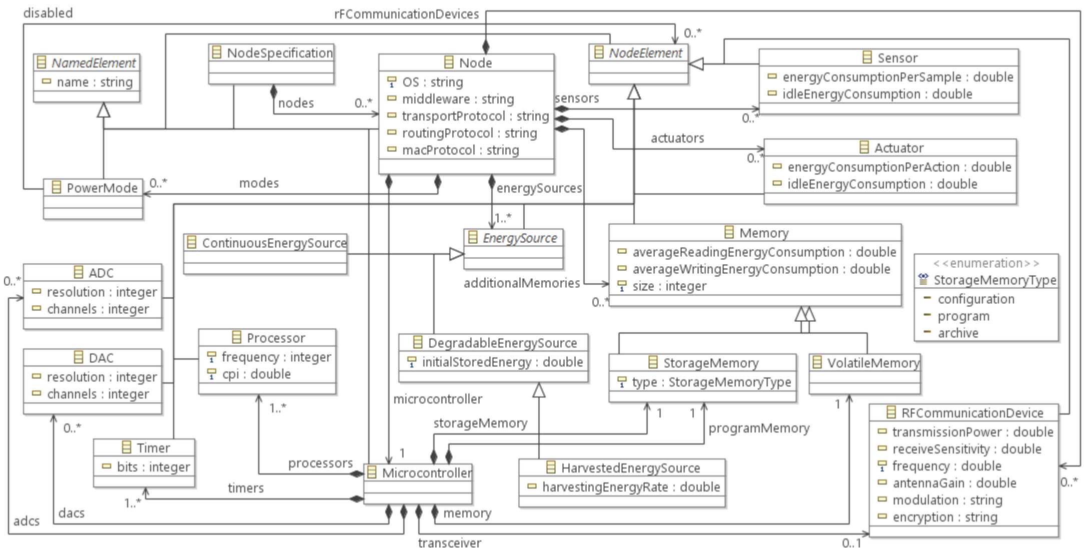

Fig. 13 NODEML Metamodel

Appendix B: The components of the Programming Framework

Figure 17 shows an overview of the A4WSN programming framework. All the boxes within the programming framework represent the various components of the generic programming workbench, whereas the $C_1..C_n$ and $A_1..A_n$ boxes represent third-party code generation and analysis plugins, respectively. Third-party plugins extend the *Code Generation Manager* and *Analysis Manager* components which provide the needed extension points and they communicate with all the other components of the

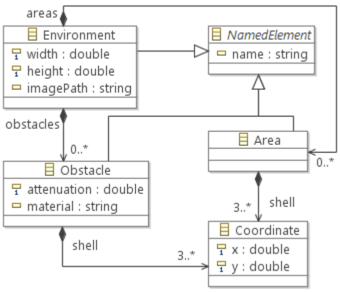

Fig. 14 ENVML Metamodel

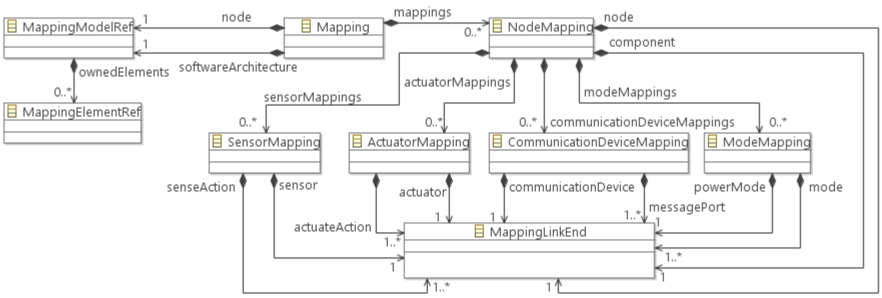

Fig. 15 MAPML Metamodel

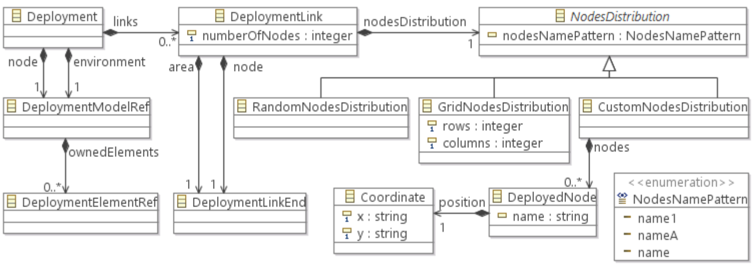

Fig. 16 DEPML Metamodel

programming framework (for the sake of clarity we do not show those connectors in the figure). In the following we will discuss the facilities and duties of the various components of the generic A4WSN programming framework, an overview of their implementation details is provided in Section 8.

Models

The central element of the programming framework is the Models repository that stores all the WSN models developed by architects and designers. Indeed, stored

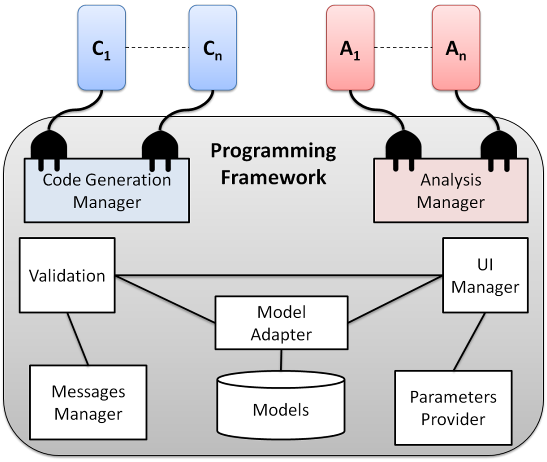

Fig. 17 The A4WSN programming framework

models can conform to any modelling language described in Section 4 which are SAML, NODEML, ENVML, MAPML, and DEPML. The models repository can be realised in different ways. For instance it may directly rely on the file system of the machine running the A4WSN platform (this is the solution implemented in the current version of the A4WSN tool), it may point to resources stored in the cloud or it may refer to some in-memory models representation. If on one side this feature of the models repository is very flexible in terms of resources consumption and localisation, on the other side it opens for possible problems of interoperability between all the other components of the A4WSN programming framework. This is exactly why the Model Adapter component exists.

Model Adapter

The model adapter is a component which abstracts the nature of the models repository to the other components of the A4WSN programming framework. The model adapter is composed of a set of connectors (each of them tailored to a specific models storage type) that expose a common interface to all the other components to access various elements of the models in a homogeneous way. Also, the Model Adapter component has a built-in model transformation, called *Merger*, that can merge linked models defined in the A4WSN modelling environment. If we consider *Merger* as a function, it can be defined as follows:

$$Merger\colon MM_{SAML}\ x\ MM_{NODEML}\ x\ MM_{ENVML}\ x\ MM_{MAPML}\ x\ MM_{DEPML} \rightarrow MM_{merge}$$

where each MM_x is the metamodel of the x modelling language, where x can vary between $SAML$, $NODEML$, $ENVML$, $MAPML$, $DEPML$, and MM_{merge} is the union of all the MM_x metamodels. In other words, *Merger* takes as an input an instance of each modelling language defined in the A4WSN modelling environment and provides a single model conforming to a unique metamodel as an output. The reason behind the existence of the Merger transformation is that currently many approaches and tools for code generation and analysis assume to have a single model as an input, rather than a set of models conforming to different languages. In order to alleviate this issue with current approaches and tools (which could have hampered the usefulness of the whole A4WSN platform), we decided to implement the Merger as an internal transformation to merge separate models into a single one. Merger can be executed at any time by plugin developers by calling a dedicated Java method.

Validation

The Validation component executes all the operations to validate A4WSN models:

- it checks whether one of the A4WSN models conforms to its corresponding metamodel (metamodels are described in Section 4);
- it executes all the OCL constraints defined in each metamodel within the A4WSN platform and checks whether they are satisfied or not;
- if defined, it executes the additional OCL constraints that are defined in some code generation or analysis plugin and checks whether they are satisfied or not.

The result of a validation operation is composed of four main elements: (i) a boolean value representing whether the involved model passes all the checks listed above, (ii) a set of informative messages that describe the result of the validation in a human-readable way, (iii) a set of in-memory representations of all the elements in the models which do not satisfy some of the checks listed above, and (iv) a set of actions that can be executed by the A4WSN platform as a quick fix of the identified violations (quick fix operations can be defined in the plugins extending the A4WSN platform).

The Validation component communicates with Model Adapter in order to access various elements of the models to be validated. Also, it communicates with the Messages Manager and the UI Manager components to show the informative messages belonging to M to the user and to highlight the elements in their graphical editor violating the constraints, respectively.

Messages Manager

The Messages Manager component serves to graphically show informative messages to the user. A4WSN supports three kind of informative messages which are *error, warning and information*. Plugin developers can decide the type of each message to be shown, depending on its severity. Each message is defined as a couple $< K, T >$, where K represents the type of message (i.e., error, warning, or information) and T represents the textual content of the message in a human readable way.

UI Manager

The UI Manager component is responsible for the main facilities interacting with the user interface of the A4WSN platform[9]. The UI Manager component provides all the graphical facilities to interact with the plugins and elements of the A4WSN platform, which are:

- *Code Generation Engines View*: a dedicated view showing a list of all the available code generation engines (with their description, icon, name, etc.), together with their management facilities, such as code generation activation, code generation results viewer, etc.;
- *Analysis Engines View*: a dedicated view showing a list of all the available analysis engines (with their description, icon, name, etc.), together with their management facilities, such as analysis activation, analysis results viewer (significantly different from the code generation results viewer), etc.;
- *Code Generation Contextual Menu*: a contextual menu that triggers the execution of a code generation engine. A contextual menu is associated to each model of the A4WSN modelling environment;
- *Analysis Contextual Menu*: a contextual menu that triggers the execution of an analysis engine. A contextual menu is associated to each model of the A4WSN modelling environment;
- *Validation Trigger*: a contextual menu and a dedicated button in the graphical editor of each model of the A4WSN modelling environment that triggers the validation of the current model. Optionally, the user can identify which plugin contains additional constraints to be checked. The results of the triggered validation are managed by the Messages Manager component;
- *Code Generation and Analysis Progress Feedback*: provides an element in the UI that graphically shows the progress of the triggered code generation or analysis. A4WSN provides two types of progress feedback, a progress bar for activities in which all the steps are known a priori and a round indicator for activities with an unknown length.
- *Plugin Additional Parameters View*: provides a dedicated view in which users can provide additional parameter to be passed to the code generation or analysis engine being triggered. Plugin developers can specify the number, name, and type of those parameters by using a specific extension point.

Parameter Provider

Parameter Provider component manages the additional parameters that a code generation or analysis plugin may require for carrying on its activities. As previously mentioned, additional parameters are defined by using a specific extension point of the A4WSN programming framework; each parameter is defined as a triplet $< name, T, default >$, where $name$ is the unique name of the parameter, T is the

[9] Also the Messages Manager interacts with the UI of the A4WSN platform, however its impact to the UI is much more limited than that of UI Manager.

type of the parameter, and $default$ is the optional default value of the parameter. Available parameter types are listed below.

- *String*: a textual value;
- *Integer*: an integer numerical value;
- *Float*: a decimal numerical value;
- *Boolean*: a boolean value;
- *Local Resource*: a file in the local file system of the user, it is referenced by its path in the file system;
- *Remote Resource*: a resource in the cloud that can be accessed by a standard HTTP GET request and is referenced by its URL.

Once the user has provided the values of the additional parameter of a code generation or analysis engine, the Parameter Provider component makes them available to the plugin realizing the engine so that it can access them before actually executing the activity which is being triggered by the user.

Code Generation Manager

The Code Generation Manager provides a set of facilities for managing code generation engines and the extension point that is used by code generation plugin developers (see Section 8 for more details). For instance it checks which plugins are currently extending its extension point and makes their facilities available to the end user. It includes all the registered code generation plugins into the *Code Generation Engines View* of the UI Manager. It loads plugins into the contextual menus of the A4WSN modelling environment. It automatically triggers the validation operations defined by the plugins before executing the actual code generation operation. Also, the Code Generation Manager component exposes a common *Java API* to plugin developers, so that they can easily interact with all the other components of the A4WSN programming framework. For example, it allows developers to access elements of the models in the Models Repository to push messages to the end user via the Messages Manager and it makes the additional parameters provided by the end users accessible directly as Java objects.

Analysis Manager

The internal logic of the Analysis Manager component is analogous to that of Code Generation Manager. The only difference is that it is designed for analysis plugins, rather than for code generation plugins. Due to its similarity to Code Generation Manager, the reader can easily grasp its functioning from the description of the latter, so we will not describe the Analysis Manager component in this paper. In Section 8 we discuss the extension points that are available to code generation and analysis plugin developers.

Extension Points

The concept of extension point is nicely described in the Eclipse Wiki[10], it says that *the extension point declares a contract, typically a combination of XML markup and Java interfaces, that extensions must conform to. Plug-ins that want to connect to that extension point must implement that contract in their extension. The key attribute is that the plug-in being extended knows nothing about the plug-in that is connecting to it beyond the scope of that extension point contract. This allows plug-ins built by different individuals or companies to interact seamlessly, even without their knowing much about one another.* The last part of the Eclipse definition of extension point says exactly what we are demanding to the WSN research community, i.e., not to rebuild the wheel by focussing on modelling languages, graphical editors, etc., but rather to focus on code generation and analysis of WSN applications by developing A4WSN plug-ins.

Table 3 shows various extension elements that can be set by third-party developers with their plugins. For each element we specify its name, whether it belongs to the code generation (column titled *CG*) or analysis extension point (column titled *A*), and a description about how it will be used by the generic A4WSN programming framework.

The extension points defined in the A4WSN programming framework are used to group code generation and analysis engines into two different groups, so that the end user knows where those engines can be found. Also, they are used to provide a common, standard behaviour to various engines that may be defined upon the A4WSN modelling environment. Both the Code Generation Manager and Analysis Manager provide a standard management of the workflow that must be followed when executing those engines. For example, they automatically call the pre-actions defined by using the *Pre Action* element of the previously defined extension point (the same holds for the post-action). Automatically manage the success and error messages to be shown after the execution of either a code generation or analysis operation, automatically update the UI of the modelling framework depending on the available plugins extending A4WSN, etc. Moreover, since plugin developers must comply with to the extension points defined in the A4WSN programming framework, they will be more keen to provide engines that are straightforward to integrate and with common basic functionalities, thus easier to use by end users. Section 6 describes an example of plugin for estimating the energy consumption of a WSN, it will be applied to our case study in the health care domain.

Appendix C: implementation of A4WSN

We make the current prototype of the proposed approach available to the community as an open-source product with MIT license in order to allow other researchers to use

[10] http://wiki.eclipse.org/FAQ_What_are_extensions_and_extension_points\%3F

Element	CG	A	Description
Name	✓	✓	The name of the engine being provided which will be shown in the engines view and contextual menus.
Icon	✓	✓	An image icon of the engine being provided which will be shown in the engines view and contextual menus.
Description	✓	✓	A textual description engine being provided which will be shown in the engines view.
Network Access	✓	✓	A boolean for declaring whether the engine uses the network for its operations which will be shown in the engines view.
Operation Time	✓	✓	An estimation of the time needed to complete the operation being defined which will be shown in the engines view.
Target Languages	✓	-	A list of the target implementation languages which will be shown in the engines view and contextual menus.
Target Path	✓	-	The path in the file system (local to the location of the plugin) to which the generated code will be saved.
Analysis Type	-	✓	A list of the properties that will be checked during the analysis operation (e.g., performance, security, etc.); it will be shown in the engines view.
Keep Intermediate	-	✓	A boolean value (optionally a path in the file system) to specify whether (and where) the analysis engine keeps possible intermediate resources.
Additional Parameters	✓	✓	A list of parameter types definition that will be used by the Parameter Provider component of A4WSN.
Validation Constraints	✓	✓	A list of OCL constraints, together with their informative messages and quick fix operations that must be used by the Validation component of A4WSN.
Pre Action	✓	✓	A reference to a Java class defining the method that will always be called before executing the engine being provided.
Post Action	✓	✓	A reference to a Java class defining the method that will always be called after the engine being provided is executed.

Table 3 Elements of the extension points for code generation or analysis plugins

the modelling languages introduced in Section 4 as well as the programming framework described in Section 5. The current prototype of A4WSN can be downloaded from the A4WSN website (http://a4wsn.di.univaq.it).

We implemented the proposed approach by extending the **Eclipse** platform[11]. Eclipse is an open-source development platform comprised of extensible frameworks and tools for building, deploying and managing software across the life cycle. We decided to use Eclipse as starting point for our modelling environment for three main reasons. First, many extensions already exist covering some aspects of our approach (e.g., graphical syntax definition for newly created languages, models persistence support, etc.). Second, its plugin architecture allows us to provide a set of extension points that other developers can use to extend our modelling framework,. Third, the Eclipse community is widely spread throughout the world, raising the possibility of adoption of our modelling environment.

For what concerns the modelling languages, model-driven engineering techniques are used to define their concepts, and their modelling environment. More specifically, we specified the static semantics of the languages by means of their underlying metamodels. Those metamodels are defined by using the **Eclipse modelling Framework** (EMF)[12], that is a Java framework and code generation facility for building tools and

[11] Eclipse project Web site: www.eclipse.org.

[12] EMF project Web site: http://www.eclipse.org/modeling/emf/.

other applications based on a metamodel. The concrete syntax of the modelling languages has been defined by using the **Graphical modelling Framework** (GMF)[13], a model-driven approach to generate graphical editors in Eclipse.

The intermediate modelling languages (i.e., MAPML and DEPML) are technically called weaving models. Weaving models are special kinds of models for defining relations among other models and to establish semantic links among model elements. Weaving models have been successfully used in many fields, such as software architecture [42] and software product lines [12]. We use the **Atlas Model Weaver (AMW)** [18] for managing those weaving models.

For what concerns the programming framework, we implemented it as a set of **Eclipse plugins**, each one implementing a single component of the programming framework, as it is depicted in Figure 17. Those plugins are implemented in Java and their dependencies are realized by means of the plugins management system provided by Eclipse. Each plugin declares the others it depends on and configuration parameters via a specific XML configuration file. The communication among plugins is handled by standard Java calls. Also, the code generation framework and the analysis framework provide two extension points dedicated to code generation and analysis plugins, respectively. The signatures of those extension points are defined in the same XML configuration files used for defining the dependencies between plugins, whereas their implementation is defined as Java classes referenced by the XML configuration files. For the sake of brevity, we do not provide the details on how the programming framework works and on how its plugins interact. A detailed description of those aspects can be found in the Eclipse plugin developer guide[14].

[13] GMF project Web site: http://www.eclipse.org/modeling/gmf/.

[14] Eclipse Platform Plug-in Developer Guide: http://help.eclipse.org/helios/index.jsp