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A Distributed Reasoning Platform to Preserve Energy in Wireless Sensor Networks

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Abstract. A distributed reasoning platform is presented to reduce the energy consumption of Wireless Sensor Networks (WSNs) offering geospatial services by minimizing the amount of wireless communication. It combines local, rule-based reasoning on the sensors and gateways with global, ontology-based reasoning on the back-end servers. The Semantic Sensor Network (SNN) Ontology was extended to model the WSN energy consumption. One exemplary prototype is presented, namely the Garbage Bin Tampering Monitor (GBTM).

1 Introduction

The GreenWeCan [1] project investigates a “green” wireless city access network infrastructure able to offer geospatial services by aggregating data from multiple sources, in a scalable and cost-effective way, and minimizing energy consumption as well as the human exposure to electromagnetic radiation. The machines in a WSN range from heavily resource-constrained sensors to powerful back-end servers. These WSNs often use a hierarchical approach with a sink that interconnects the sensors and the back-end. Power management is important in WSNs. Sensors are often battery-operated, so their autonomy must be maximized. As radio transmissions needed for communication are costly operations [2], it is often beneficial to carry out as much processing as possible on the node itself.

Therefore, a distributed reasoning platform (Section 2) was utilized. Rule-based reasoning on the sensors allows for conclusions concerning measured variables to be drawn locally. A back-end ontology-based reasoning mechanism, which has a complete overview of the senor data being produced, can influence the behavior of the WSN nodes. Section 3 describes the ontology, which is used to model and reason on the sensor knowledge to reduce energy consumption.

The use of proven standard reasoning mechanisms in WSNs is still premature. However, the reduction in energy consumption by a reduced transmission rate, compared to the extra power needed for such processes, should result in a positive balance. Moreover, using standard reasoning algorithms, instead of proprietary ones, makes the approach more generic and facilitates reusability. A prototype was developed to demonstrate these advantages (Section 4).

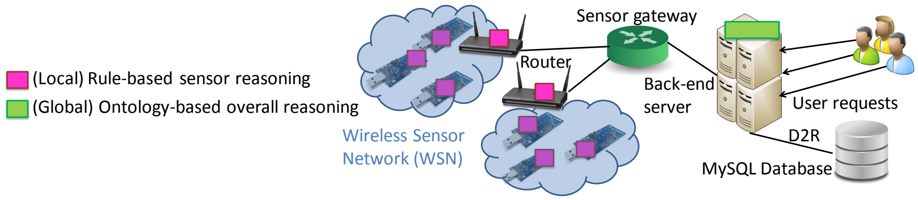

Fig. 1. Reasoning Architecture of the WSN

2 Reasoning architecture

As shown in Figure 1, information requested by the users is gathered from the sensors, which measure environmental parameters and pre-process them by performing rule-based reasoning. As such, less data is transmitted to the back-end. The complexity of the local reasoning can be adapted to the sensor's capabilities, e.g., battery, to optimize energy consumption. Moreover, the local reasoning is able to monitor the sensor's inner workings, e.g., CPU usage, in order to detect problems that influence energy consumption.

The pre-processed data is forwarded to the back-end via a gateway, optionally multi-hopping over routers. The sinks perform local, rule-based reasoning, e.g., to avoid retransmissions and preserve energy, the network load is monitored.

The back-end maintains an ontology to model the knowledge about the WSN and its observations. Static information, e.g., sensor specifications, is gathered from a database using D2R[3]. The received sensor data is integrated into this ontology to answer user requests and optimize the overall energy consumption.

Using an ontology ensures reusability and adaptability. Should new types of sensors be deployed, their semantic description and measurements can be mapped on the existing ontology. Moreover, by making the ontology publicly available as well as the data and conclusions corresponding to the run-time situation of the WSN, new applications can be created by anyone persuing a new usage and easy integration of this information.

The ontology can also be used to define the local, rule-based reasoning algorithms. The developed *Reasoning Sensor App Generator* generates sensor application code based on an XML-based application description. This description specifies a rule set and a template. The first contains the reasoning logic, which is executed each time the sensor wakes up. The second contains the code needed to run the reasoning logic on hardware.

3 A SSN Ontology extension modeling energy usage

The W3C Semantic Sensor Network Incubator group has developed the SSN Ontology[4] for modeling sensor devices and their capabilities, systems and processes. Based on brainstorms with GreenWeCan partners, i.e., OneAccess and Bausch Datacom, the requirements for the modeling concepts were defined. These were mapped on the SSN Ontology and some extensions were made. The relations

[3] `http://d2rq.org/d2r-server`
[4] `http://www.w3.org/2005/Incubator/ssn/ssnx/ssn`

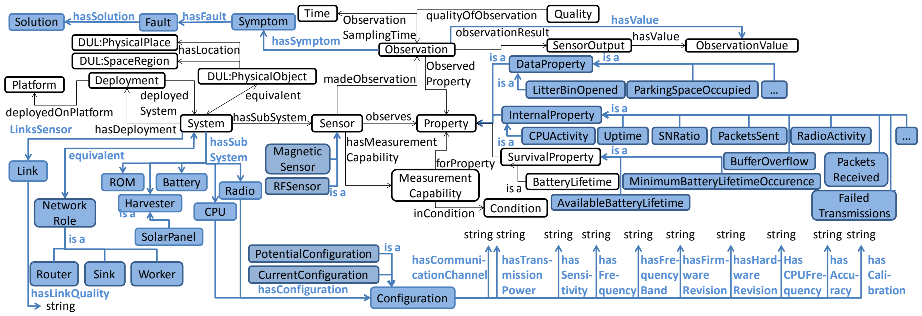

Fig. 2. The SSN Ontology extended (indicated in blue) to model energy consumption

between the sensor configurations, networks and applications and the influence on the energy consumption were also derived.

As shown in Figure 2, the SSN Ontology allows to model sensors, their observations and measurement capabilities. To avoid error propagation and retransmissions, the SNN was extended with concepts to make the quality of the observations explicit as they can be imprecise, ambiguous or erroneous. `Symptoms` define rules, which allow detecting specific phenomena in the observations. Axioms are defined that reclassify these `Symptoms` as `Faults` and `Solutions`.

The SSN `Property` concept models the type of metrics that can be observed. The `Data-` and `InternalProperty` subclasses are added to group the application-relevant observations monitored and the hardware-specific properties internally measured by the sensor. Figure 2 shows some internal properties to minimize energy consumption, e.g., sleeping schemes and radio settings can be adjusted to avoid buffer overflows and thus the amount of retransmissions.

The type of a sensor indicates which local reasoning techniques can be adopted. The `Sensor` concept in the SSN Ontology is annotated with a reference towards SensorML[5]. This specification can be used to reflect all the sensor's details.

`Battery`, `Harvester`, `ROM`, `CPU` and `Radio` concepts are introduced as these influence the reasoning complexity that can be used. The SSN Ontology already defines the `Battery LifeTime` property. Some other battery properties were added. The `Current-` and `Potential Configurations` of the radio and CPU are also modelled. The first models the currently used values for the characteristics, while the second represents the combination of values that can potentially be used together. Similarly, new sensors can be modeled, as shown in Figure 2 for the `Magnetic Sensor` and its settings, e.g. `Sensitivity`.

The location of the sensors can influence the energy consumption. The SSN Ontology models the WSN's deployment. To represent the physical locations the SSN Ontology aligns with the DOLCE Ultra Lite Ontology[6]. These concepts are preceded by the *DUL* namespace in Figure 2. `Link` and `NetworkRole` concepts are introduced to represent the network components used to interconnect the

[5] `http://www.opengeospatial.org/standards/sensorml`
[6] `http://www.loa.istc.cnr.it/ontologies/DUL.owl`

nodes and the role each node plays. Characteristics can be attached to the links, e.g., `LinkQuality`, which influences packet drops and retransmissions.

Finally, the context in which the WSN operates plays a role. Therefore, the ontology is linked to existing ones, e.g., the OWL Time ontology and DBPedia[7].

4 Garbage Bin Tampering Monitor Prototype

The GBTM monitors garbage bins in Ghent, which are used for small-scale litter disposal and are equipped with a sensor to detect the opening and closing of their cover. The cover can only be removed by a special-purpose key. Any other manipulations are illegitimate. A web-based interface[8] allows personnel to consult the observations, either as raw data, as an alligned table clustering data per bin or on a map. Anomalies are highlighted by combining the observations with external data, e.g., garbage collection timetables. The views also allow optimizing garbage collection routes and timetables.

Rule-based sensor reasoning The garbage bins are equipped with a magnet-activated reed switch, which stores a type, i.e., open or close, and timestamp in the sensor's ROM when a hardware interrupt occurs. To reduce the number of transmissions, rule-based reasoning accumulates the sensor readings during a configurable time interval, after which they are transported in bulk to a database on the back-end server, which exposes them via a D2R-based RESTful interface.

Ontology-based back-end reasoning The sensors issue their measurements once per time interval to the back-end. The *Next-Wake-Up-Time* configuration parameter determines the timepoint at which this happens. It is preferably avoided that sensors wake up at the same time as this increases the amount of retransmissions, particularly in single-hop topologies, due to collisions. Therefore, if such a situation is discovered, the back-end reasoner will use the WSN ontology to recalculcate a dephazed next wake-up time scheme.

Rule-based gateway reasoning When the gateway receives a request, it first checks if the required up-to-date info is available in its cache. If it is, the cached data is sent to back-end to reduce the amount of data transmitted and thus the energy consumption. If not, the measurements are retrieved from the sensors. Determining the time after which data in the cache should be refreshed is difficult. Applications preferably use the most recent measurements. However, they need to comply with legislation concerning how much Radio Frequency communication is used, e.g., 6 minutes per hour for a 169 MHz radio. Therefore, the gateway monitors the duty cycle and adapts its caching strategy accordingly.

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2. P. De Mil, et al.: Design and implementation of a generic energy-harvesting framework applied to the evaluation of a large-scale electronic shelf-labeling wireless sensor network. EURASIP JWCN (2010) 12

[7] `http://www.w3.org/TR/owl-time/` & `http://wiki.dbpedia.org`

[8] `http://mediasharing2.edm.uhasselt.be/greenwecan_v3/php/gwc_usecase_gbtm.php`