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Technical Report

On the Development of a Test-Bed Application for the ART-WiSe Architecture

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Abstract

The ART-WiSe (Architecture for Real-Time communications in Wireless Sensor Networks) framework aims at the design of new communication architectures and mechanisms for time-sensitive Wireless Sensor Networks (WSNs). We adopted a two-tiered architecture where an overlay Wireless Local Area Network (Tier 2) serves as a backbone for a WSN (Tier 1), relying on existing standard communication protocols and commercial-off-the-shell (COTS) technologies – IEEE 802.15.4/ZigBee for Tier 1 and IEEE 802.11 for

Tier 2. In this line, a test-bed application is being developed for assessing, validating and demonstrating the ART-WiSe architecture. A pursuit-evasion application was chosen since it fulfils a number of requirements, namely it is feasible and appealing and imposes some stress to the architecture in terms of timeliness. To develop the testbed based on the previously referred technologies, an implementation of the IEEE 8021.5.4/ZigBee protocols is being carried out, since there is no open source available to the community. This paper highlights some relevant aspects of the ART-WiSe architecture, provides some intuition on the protocol stack implementation and presents a general view over the envisaged test-bed application.

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The ART-WiSe (Architecture for Real-Time communications in Wireless Sensor Networks) framework aims at the design of new communication architectures and mechanisms for time-sensitive Wireless Sensor Networks (WSNs). We adopted a two-tiered architecture where an overlay Wireless Local Area Network (Tier 2) serves as a backbone for a WSN (Tier 1), relying on existing standard communication protocols and commercial-off-the-shell (COTS) technologies – IEEE 802.15.4/ZigBee for Tier 1 and IEEE 802.11 for Tier 2. In this line, a test-bed application is being developed for assessing, validating and demonstrating the ART-WiSe architecture. A pursuit-evasion application was chosen since it fulfils a number of requirements, namely it is feasible and appealing and imposes some stress to the architecture in terms of timeliness. To develop the test-bed based on the previously referred technologies, an implementation of the IEEE 8021.5.4/ZigBee protocols is being carried out, since there is no open source available to the community. This paper highlights some relevant aspects of the ART-WiSe architecture, provides some intuition on the protocol stack implementation and presents a general view over the envisaged test-bed application.

1 The ART-WiSe architecture

1.1 General aspects

The ART-WiSe (Architecture for Real-Time communications in Wireless Sensor networks) framework [1,2] aims at providing new communication architectures and mechanisms to improve the timing and reliability performance of Wireless Sensor Networks (WSNs). The ART-WiSe architecture is based on a two-tiered network structure (Fig. 1) where a wireless network (Tier 2) serves as a backbone for a WSN (Tier 1), relying on standard communication protocols and commercial-off-the-shell technologies – IEEE 802.11 [5] for Tier 2 and IEEE 802.15.4/ZigBee [3,4] for Tier 1:

- **Tier-2** is an IEEE 802.11-compliant network acting as a backbone for the underlying sensor network. It is composed of a scalable set of special nodes called *Access Points*, which act as interfaces between the two tiers. Each Access Point must also act as a Personal Area Network (PAN) coordinator of the IEEE 802.15.4 Wireless PAN (WPAN) it manages.
- **Tier-1** is an IEEE 802.15.4-compliant WSN interacting with the physical environment (e.g. to collect sensory data). This WSN is partitioned into several independent WPANs, each of them managed by one Access Point. Each WPAN may still be structured into multiple clusters, whenever the density/location of the Access Points does not provide direct coverage for the WSN nodes.

The IEEE 802.15.4 protocol [3] is characterized by a low data rate (250 kbps), a short transmission range (10-30 m) and a low power consumption, thus leading to limited communication capabilities. We have been characterizing its timing behaviour in several research works (e.g. [9-10]), both via analytical and simulation tools. This protocol has several appealing features to fulfil different requirements of sensor network applications. Besides the best-effort Slotted CSMA/CA MAC protocol, it enables WSN nodes to reserve Guaranteed Time Slots (GTS), therefore leading to bounded communication latencies. We are also assessing the adequateness of the ZigBee protocol for (large-scale) WSNs, namely for the ART-WiSe architecture. Within this trend, we have identified a number of ambiguities and open issues existent in the ZigBee standard, and are working on solutions to these problems, namely on tackling beacon synchronization and hidden-nodes in multiple cluster topologies (e.g. cluster-tree).

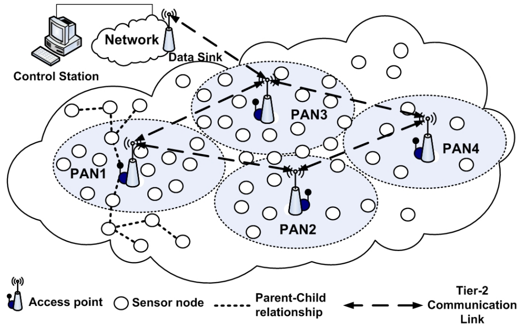

Fig. 1. Example of the ART-WiSe network topology

IEEE 802.11 is envisaged for Tier 2, since it is widely used, very mature and represents a cost-effective solution with powerful networking capabilities, high bandwidth (11-54 Mbps) and long transmission ranges (>100 m). Although the basic IEEE 802.11 does not provide any Quality of Service (QoS) guarantees, it has been shown that it performs well under lightly loaded networks [6,7]. In ART-WiSe, it is expected that the overlay network will not be subject to highly loaded situations, since the difference between data rates in the Tier 1 and in the Tier 2 is quite high. Moreover, the use of the IEEE 802.11e extension [8], that provides additional QoS guarantees to the IEEE 802.11 protocol, is also planned. Some aspects of the Tier 2 network (e.g. ad-hoc/structured, data fusion, routing) are still under evaluation.

1.2 Sensor node and access point architecture

Two basic types of nodes are considered in ART-WiSe: the *sensor node*, and the *access point* node (Fig. 1). The former (also referred to as a *Tier-1 node*), represents a simple sensor node with limited processing, sensing and radio communication capabilities. The latter (also referred to as a *Tier-2 node*) represents a node with more powerful networking capabilities. The access points

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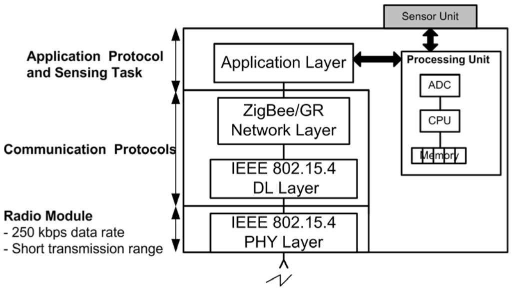
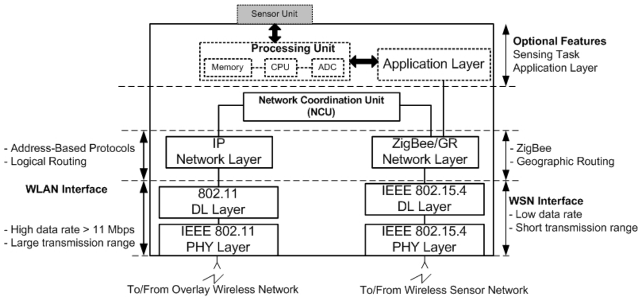
primarily act as intermediate systems relaying traffic between the two tiers.

Fig. 2 presents the internal architecture of sensor (Fig. 2a) and access point nodes (Fig. 2b).



a) Sensor Node Model



b) Access Point Node Model

Fig. 2. ART-WiSe nodes architecture

The *sensor node* is composed of a *Sensor Unit*, which interacts with the physical environment (e.g. sensing task), a *Processing Unit* that performs the required processing (e.g. aggregation, analysis, interpretation) of the sensory data, an *Application layer* that provides an interface between the sensing task with the communication protocols, a routing protocol (e.g. ZigBee), and IEEE 802.15.4 Data Link and Physical layers.

An *access point* must bring together the communication functionalities of both Tier-1 and Tier-2 networks to perform the relaying functionality. Thus, it comprises two network interfaces: (1) the *WSN Interface,* which consists of a radio module and a data link layer enabling the communication with the sensor nodes; (2) the *WLAN Interface*, which consists of a radio module and a data link layer enabling the communication with the overlay wireless network. This interface is in charge of relaying sensory data across the Tier-2 network towards the data sink. The IEEE 802.15.4 interface must provide the adequate services for each access point to act as a PAN coordinator within its WPAN.

The basic operation of an access point is to gather data from the sensor nodes on the WSN interface and forward it to via its WLAN interface. However, the Network Layers of both networks may be incompatible. In fact, in our basic ART-WiSe architecture, where IEEE 802.11 is assumed as the overlay network, the IP (Internet Protocol) protocol may be used as the routing protocol. In this case, an incoming packet from the WSN is routed using ZigBee or a geographical-location (GR) based scheme, which are not compatible with the IP protocol. Therefore, the access point must incorporate a *Network Coordination Unit* (NCU), whose purpose is to perform translations from one routing information format to another and to rearrange packet formats. An access point may optionally feature sensing capabilities, to directly sense the physical environment.

2 Implementation of IEEE 802.15.4

2.1 General aspects

ZigBee is currently a buzzword. However, there a few things that most people interested in these areas are not aware of. First, the members of the ZigBee Alliance [11] form a strong commercial lobby, currently (only) focusing on the home automation market. Second, there are some ambiguities and open issues in the ZigBee specification [4], namely how to engineer beacon synchronization/scheduling in cluster-tree networks. Third, there is no open source code available to the community, neither for the ZigBee (Application and Network Layers) nor for the IEEE 802.15.4 (Physical and Data Link Layers) protocols. Moreover, companies selling “IEEE 802.15.4-compliant” motes (e.g. MICAz [14]) are not fully honest to the consumer, since these devices only provide the Physical Layer services. Therefore, the IEEE 802.15.4 Data Link Layer protocol, namely the Medium Access Control (MAC) mechanism, is not provided.

These issues triggered our motivation for developing a full implementation of the IEEE 802.15.4 protocol, by providing an organized, well documented and open-source implementation of the standard in nesC for TinyOS [13]. One of the first lessons learned from this development effort is that current MAC protocol implementations for TinyOS are quite complex (the OSI layered model is not respected) and do not provide sufficient supporting documentation. We are implementing the IEEE 802.15.4 protocol for the Crossbow MICAz motes [14]. These “IEEE 802.15.4-compliant” motes operate in the 2,4 GHz ISM band and have a 16 Mhz Atmel ATMega128L microcontroller (with 128 kB of program Flash) [15] and a Chipcon CC2420 802.15.4 radio transceiver (allowing a 250 kbps data rate) [16].

Since we are designing a scalable two-tiered architecture with a variable/dynamic number of access points, there will be the need for a routing protocol for the Tier 1 network. For this, we are analysing different alternatives, namely the routing protocols defined in the ZigBee standard. In this context, we are starting the implementation and assessment of the ZigBee cluster-tree routing protocol based on the same technological platform.

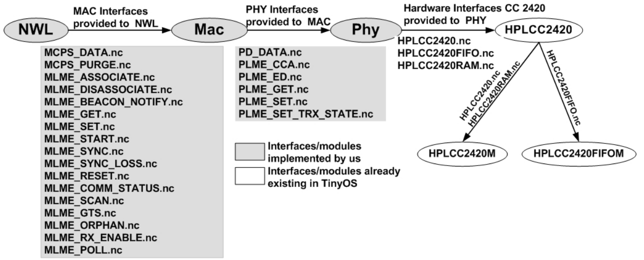
2.2 Implementation approach

The main tasks of the Physical Layer are: (1) the activation/deactivation of the radio transceiver; (2) energy detection within the current channel; (3) transceiver data management, Received Signal Strength Indication (RSSI) readings and channel frequency selection; (4) Clear Channel Assessment (CCA) procedure for the CSMA/CA mechanism; (5) data transmission and reception management.

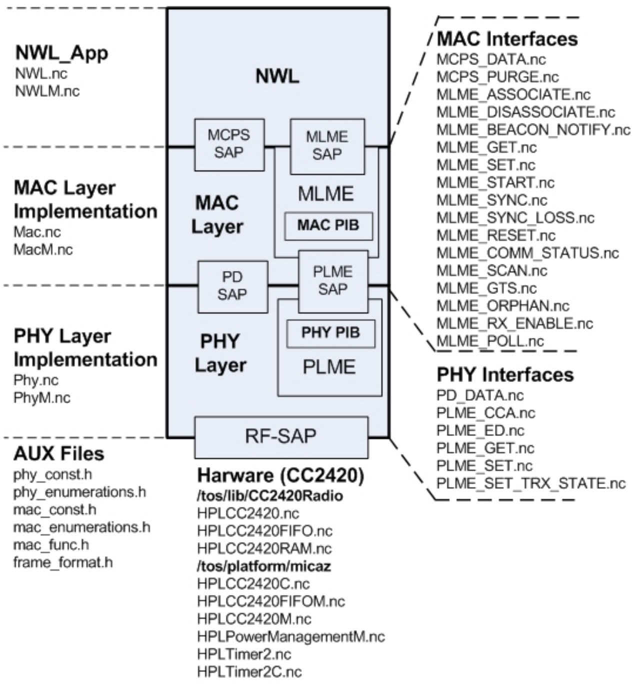
On the other hand, the MAC protocol must provide the following functionalities with respect to the standard specification: (1) network beacon generation if the device is a coordinator; (2) synchronization services; (3) PAN association and disassociation procedures; (4) CSMA/CA as a contention access mechanism; (5) the GTS mechanism management; (6) security services.

Fig. 3 presents the architecture of our IEEE 802.15.4 implementation. Fig. 3.a shows the TinyOS implementation diagram, respecting the OSI layer structure presented in Fig. 3.b. Note that this organized structure was not adopted in previous default MAC implementations for MICAz motes. We are currently implementing the Physical, Data Link and Network layers (gray modules in Fig. 3.a). The hardware drivers of the CC2420 radio transceiver are already provided by TinyOS.

The PHY module is directly associated to the hardware modules that are already provided in TinyOS. The *CC2420* modules are used with no modifications. The PHY module was designed to be easily portable to other hardware platforms compliant with the IEEE 802.15.4 standard. The physical layer *Service Access Providers* (PHY SAP) and the PHY *PAN Information Base* (PHY PIB) are implemented in this module. Each PHY SAP is represented by an interface that will be used by the MAC layer. The PHY SAPs implemented in the physical layer represents the *Data Services*, which provide the exchange of data between the PHY and MAC layers, and *Management Services* that provide hardware functions and PHY PIB management procedures. The PHY PIB stores information about hardware configurations like the current and supported channels, transmit power and the CCA mode (there are three modes of CCA defined in the standard [3]).



a. TinyOS Implementation Diagram



b. Protocol Stack Architecture

Fig. 3. Protocol stack software structure

The MAC module uses the interfaces provided by the PHY module and implements the MAC SAPs, the MAC PIB and the MAC PIB Security attributes. Each MAC SAP is represented by an interface that will be used by the upper layer (e.g. Network Layer). The MAC SAPs implemented in this module are the *Data Services,* which provide data management, and the *Management Services,* which provide functions for handling network association/disassociation, synchronization, orphan devices, communication, MAC PIB, beacon forming and generation and the GTS mechanism. The MAC PIB stores information about the acknowledgement waiting duration, auto-request, battery level, node (extended and short) addresses, sequence numbers, number of backoffs and PAN address. The Full Function Devices (FFDs) [3] also store information about association permissions, beacon payload, beacon order, beacon transmit time, beacon sequence number, GTS permissions, promiscuous mode, superframe order and the transaction persistence time.

We also provided some auxiliary files ('AUX', Fig. 3b) for data structure definition, constants, enumerators and auxiliary functions) and some minor changes to the TinyOS timer modules.

3 The test-bed application

3.1 Requirements

In order to assess, validate and demonstrate the ART-WiSe architecture, a test-bed application is under development. This application must satisfy a number of requirements, namely it should:

- be as much appealing and realistic as possible, nevertheless limited to the available human and technological resources; it should include a sufficient number of WSN nodes (currently we have 25 MICAz motes) and of static and mobile Access Points (we have several PDAs, mobile robots, Single Board Computers, etc.)
- allow to assess the feasibility of the ART-WiSe architecture, based on the chosen/available technologies;
- allow to assess the real-time behaviour of the ART-WiSe architecture (tackling critical events), comparing to analytical and simulation results;
- allow to assess the scalability of the ART-WiSe architecture (adaptable density of Access Points), enabling the comparison with "traditional" 1-tiered WSNs;

3.2 Outline of the test-bed application

We are deploying a pursuit-evasion game. One of the reasons that lead us into this option was the fact that this kind of application imposes stringent timing requirements to the underlying communication infrastructure. It also involves interesting research problems in sensor networks like tracking, localization, cooperation between nodes, energy concerns and mobility. Additionally, it can easily be ported into a real-world application. Surveillance or search and rescue operations are two examples where this kind of functionality can be applied.

We are currently implementing the pursuit-evasion application using just the Tier 1 network (Fig. 4), i.e. without the Tier 2 network defined in the ART-WiSe architecture. The objective is to achieve some maturity on the used technologies and application development, in order to evolve to the two-tiered architecture in the near future.

Two different groups of mobile robots (Fig. 4) are considered: the *pursuer* team and the *intruder* team, both consisting of *off-the-shelf* mobile robots – e.g. Scribbler [17] and WifiBot [18]. The objective is to track and pursuit each intruder until a pursuer robot gets close enough to it. A control station will serve as a data sink, providing information related to the state of the application to the user level and performing the necessary data collection and processing.

The pursuer team will be aided by the WSN abilities to find the intruders. The system must be able to distinguish between the two teams and provide real-time positioning/tracking of moving robots. Each WiFiBot has an embedded Linux system and an IEEE 802.11 interface (to act as access points – Tier 2). A MICAz mote [16] was deployed on top of each WiFiBot for interfacing to the WSN (Tier 1). Communication between the MICAz and the WiFiBot is currently made via a RS-232 interface. The intruder team consists of smaller mobile robots (e.g. the Scribbler [17]) with no interaction with the network (neither with Tier 1 nor with Tier 2).

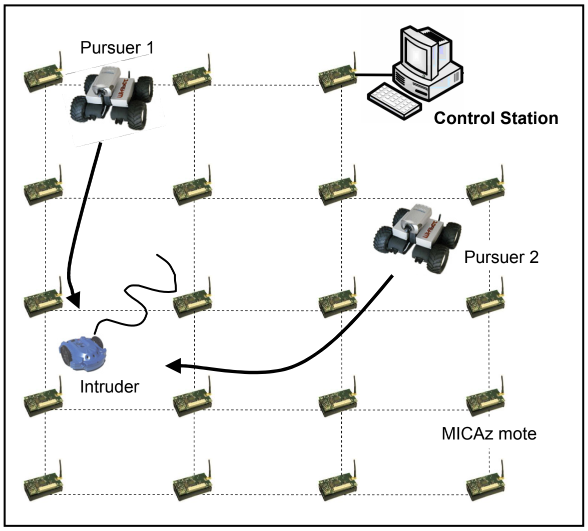


Fig. 4. Current test-bed application scenario

As shown in Fig. 4, the WSN is composed of MICAz motes [16] deployed in a grid topology in an indoor environment. One of the issues currently being tackled is the localization of the pursuer group with the sensor network. There are many proposals on this subject using different kinds of range measurements, like Time of Arrival (ToA) or Radio Signal Strength (RSS). For instance, the Cricket [19] indoor localization system uses ToA obtained by combining ultrasound and RF measurements, whereas MoteTrack proposed in [20], uses RSS measurements to provide location signatures for each node in the network.

We have opted for the RSS range measurement method to enable a simple localization scheme based on a trilateration algorithm running in a pursuer mobile robot or in the control station. Since this range measurement method does not involve special hardware design, it can easily be implemented in the MICAz mote. Our experiments show that it is possible to locate a pursuer robot with this kind of ranging method, with an acceptable accuracy. Due to the restricted geographical area imposed by our indoor environment, we rely on the lowest transmission power level of the MICAz mote, since with higher transmission power levels we found almost impossible to infer the distance from the RSS measurements.

Our current scenario consists of a grid of motes where their absolute positions are statically assigned pre-run-time. Whenever the control station needs to identify the position of a pursuer robot, it sends a trigger message to the robot. The latter broadcasts a message to the sensor network (using low power level) that will only be received by the closest nodes. Then, these nodes transmit their positions and corresponding RSS values to the control station, through the sensor network. The pursuer robot position is computed by the control station (based on at least three RSS measurements), that transmits the appropriate actions back to the pursuer robots (through the sensor network), based on the positions of the intruders (that must also be determined in real-time). The use of magnetometers (available in the MICAz sensor boards) is envisaged for the detection of the intruder robots.

As previously mentioned, after finalizing and performing a thorough assessment of this “classical” one-tiered WSN configuration of the test-bed application, we envisage to gradually introduce Tier 2 network nodes (access points). This methodology will enable the comparison of the performance/behaviour of a classical (one-tiered) WSN against the scalable solution provided by the ART-WiSe two-tiered architecture.

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