

On a IEEE 802.15.4/ZigBee to IEEE 802.11 Gateway for the ART-WiSe Architecture

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Abstract. *Wireless Sensor Networks (WSN) have been attracting growing interests for developing a new generation of large-scale embedded computing systems, with a great potential for a wide range of applications such as surveillance, environmental monitoring, emergency medical response or building automation. However, the communication paradigms in wireless sensor networks differ from the ones associated to traditional wireless networks, triggering the need for new communication protocols and architectures. The ART-WiSe (Architecture for Real-Time communications in Wireless Sensor Networks) framework aims at the design of a scalable multi-tiered WSN architecture for supporting large-scale embedded computing applications with critical requirements. 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. This paper outlines ongoing work on the design of the architectural requirements and features for a QoS-aware gateway between both networks.*

1. Introduction

Typically, a Wireless Sensor Network (WSN) is composed by a large number of nodes, with limited processing, sensing and radio communication capabilities, scattered throughout a certain geographical region, where the sensory data is routed in a multi-hop fashion from the originator to a remote control station. WSNs differ from other types of wireless networks due to their ubiquitous nature, large size and hardware limitations of the low-cost and low-power sensor nodes. These features turn WSNs naturally unreliable, raising additional challenges for supporting real-time and reliable communications.

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 WSNs. This 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/WiFi [3] for Tier-2 and IEEE 802.15.4/ZigBee [4,5] for Tier 1.

The gateway interfacing the two tiers, the ZigBee-Gateway (ZG), as well as the protocol stacks in the two tiers, have to be capable of fulfilling some pre-defined requirements. We believe that both protocol stacks, the IEEE 802.15.4/ZigBee in Tier 1 and the IEEE 802.11/WiFi with the IEEE 802.11e [6] extension in Tier 2 are good candidates to meet the ART-WiSe requirements.

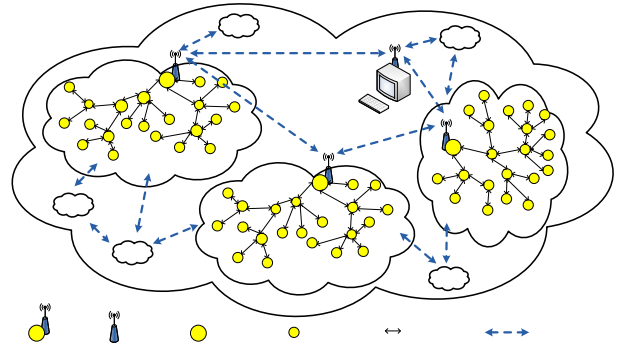


Fig. 1: Example of the ART-WiSe two-tiered architecture

The goal of this paper is to provide an overview of the architectural requirements, features and behaviour of the ZG, focusing on some specific aspects and drawing some open issues.

2. ART-WiSe Design Goals

In the following, we outline the main design goals for the ART-WiSe architecture that can be extended to the Gateway architecture: (1) *real-time performance*, predominant feature, the additional cost in terms of hardware, development, deployment and maintenance must be vindicated by guaranteeing improved real-time performance; (2) *reliability*, since the Gateways are less power-constrained, support higher data rate, have enough memory, they cannot be so error-prone as sensor nodes; (3) *scalability* the overlay WLAN must be able to deal with a large number of nodes so that its increase does not affect the behaviour of the two-tiered architecture; (4) *mobility*, adaptation to the potential dynamic changes of both Tiers topologies, moving gateways and sensor nodes, active and inactive states; (5) *load balancing*, the

network should auto adjust it self to balance the total load between all active ZG, avoiding bottlenecks. (6) *cost-effectiveness*, the two tier architecture must be cost-effective as the additional cost of hardware, deployment, development and maintenance, must be as low as possible; (7) *energy-efficiency*, an important requirement of low-power, low-communication range and low-data rate wireless devices.

3. Related Work and Motivation

Several research works and commercial products address the interoperability between WSNs and other networks (e.g. Internet). The concept of having a two-tiered architecture for WSNs is not new and can be found in different networking areas (e.g. to improve security or Quality of Service such as IP over ATM).

In reference [7], Intel Research proposed a two tiered architecture using an IEEE 802.11 mesh network as an overlay tier of a heterogeneous WSN. However, to our best knowledge, the authors have not presented any details on the coordination and communication mechanisms. Also, the choice of a basic IEEE 802.11 in DCF (Distributed Coordination Function) mode may be inefficient since it does not provide QoS guarantees.

Commercial gateways, such as [8,9] rely on IP/Ethernet for their backbone network. These approaches might be cost effective and reliable for small and static networks but the scalability for the Tier 2 is limited by the need of a physical Ethernet port for every gateway.

The authors in reference [10] propose using the gateway as a portal where each node is identified by an IP address allowing their direct access. However, there is no mobility support and the handling of very large networks may become a difficult task.

Reference [11] proposes the use of a two-tiered WSN architecture for structural health monitoring. This is a GSM-like architecture that divides the monitored area into several clusters. Each cluster is managed by a local master that handles the communication using a TDMA-like protocol inside the cluster. This approach lacks scalability inside each cluster due to the TDMA inherent limitations. Also, this architecture is entirely dependent on the presence of a local master to ensure communications, which is not suitable for WSNs. In fact, for a large-scale network, this architecture is unpractical since the number of local master's increases linearly with the number of deployed nodes, resulting in a significant increase of the overall cost.

Although most academic and commercial architectures focus several specific design features, they do not satisfy all of the proposed ART-WiSe design goals. Nevertheless, a few of them accomplish some of these features but not all.

4. Gateway Architecture

4.1. Message parsing and traffic classes

In Tier 1, the IEEE 802.15.4 medium access control (MAC) protocol enables the use of both contention-based access (CSMA/CA) and contention-free (GTS - Guaranteed Time Slots) access periods. The traffic differentiation strategy proposed in [13] permits to define two service classes in CSMA/CA, separating data flows into High Priority (HP) and Low Priority (LP).

In Tier-2, the IEEE 802.11e [6] extension defines two different MAC schemes: (1) the Enhanced Distributed Channel Access (EDCA) an enhancement of the Distributed Coordination Function (DCF), allowing increased probability of earlier transmissions of messages with higher priority, and (2) Hybrid Coordination Function Controlled Channel Access (HCCA), an enhancement of the Point Coordination Function (PCF), which is the most promising solution for QoS support but with no commercial implementation so far, to the best of our knowledge. In IEEE 802.11e, 8 priority levels of data traffic are supported.

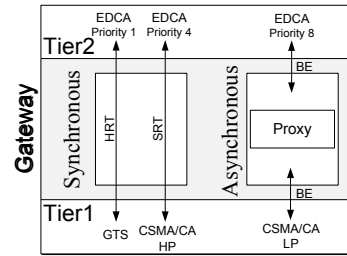


Fig. 2: ZigBee-Gateway priority levels

In our architecture we define three traffic classes (Fig.2): (1) Hard Real Time (HRT), for time critical messages using Tier 1 GTS and the Tier 2 EDCA priority 1; (2) Soft Real Time (SRT), for time sensitive messages, using Tier 1 CSMA/CA-HP and the Tier 2 EDCA priority 4; (3) Best Effort (BE), for normal messages with low priority using the Tier 1 CSMA/CA-LP and the Tier 2 EDCA priority 8. To support message parsing with traffic differentiation, the ZG has two different behaviours: a synchronous behaviour for time critical messages (HRT and SRT) and an asynchronous behaviour for normal messages (BE). As depicted in the Fig. 2., each traffic class is treated differently. The HRT and SRT messages are handled synchronously i.e relayed directly to Tier 1, while BE messages are asynchronously, handled by a proxy service.

Considering the internal operation and functionalities of the ZigBee-Gateway, we divided it into three main modules (Fig. 3): (1) ZigBee Module, supporting all functionalities associated to the ZigBee Coordinators and the Tier 1 network; (2) WiFi Module, providing all functionalities required to ensure Tier 2 WiFi

connectivity, addressing and routing; (3) Service Module, responsible for handling the ZigBee-Device Table and the proxy service.

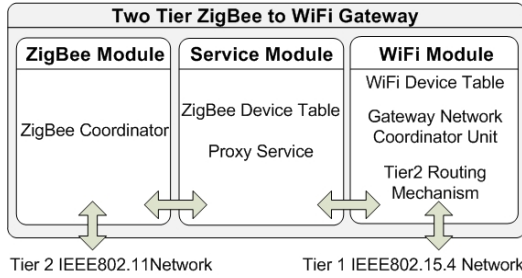


Fig. 3: ZigBee Gateway modules division

4.2. ZigBee Module

In Tier 1, we consider the case of a ZigBee cluster-tree topologies as the one exemplified in Fig. 4. One ZigBee Coordinator (ZC) identifies the entire network and each ZigBee Router (ZR) assumes the role of cluster-head allowing the association of other ZRs and ZigBee End Devices (ZEDs) in a *parent-child* relationship. There can be multiple clusters in a network, as depicted in Fig. 4. When the association process is successful, we say that the child device has joined (or associated) the network through its parent (ZR). Inside a cluster, the communication is established via the cluster-head i.e. direct communication between two children in the same cluster is not possible.

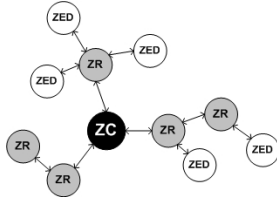


Fig. 4: The cluster-tree topology model

Basically, the main task of the ZigBee Module is to interface with the ZC. Additionally, every ZR must run an application layer program (Gateway Register) for notifying the ZG whenever a ZR child node associates, disassociates or when the connection to that node is lost. The registering process is also used to update the ZG with the node features.

4.3. WiFi Module

The WiFi module is divided into three sub-modules: (1) the WiFi-Device Table (WiFi-DT), containing information about every ZG and sink in Tier-2. This table stores the information about the PAN-IDs, ZG addresses, physical locations, Tier 1 traffic load and radio channels used; (2) the Network Coordination Unit (NCU) ensures address and message translation between both tiers; and (3) the Routing sub-module provides all routing requirements to the WiFi mesh network. We did not

address routing alternatives for Tier 2 yet, but the emerging IEEE 802.11s [14], will surely deserve our attention.

In addition the WiFi module distinguishes two types of message frames: data frames and the management frames. The former are used for data transmissions while the latter are used for gateway specific messages such as routing procedures, WiFi-DT updates and configurations.

4.4. Service Module

The Service Module is divided into two sub-modules the ZigBee-Device Table (ZB-DT) and the Proxy service. The ZB-DT is a dynamical table including Tier 1 node information provided by the WSN Gateway Register, such as: short address, extended address, parent address, physical location, battery level, current link quality, proxy data and proxy time to live. While consider the ZB-DT and the proxy services as two independent sub-modules, nevertheless the proxy service relies on the ZB-DT to store cached proxy data and to update entries. This cached proxy data is updated by the nodes using an application proxy layer program (the Sensor Proxy). This program, running on every WSN node, can be configured to periodically send data to the proxy (time triggered), respond to proxy requests (on demand) or whenever an events occurs (event driven).

5. Gateway Data Flows and Features

In this section, we overview some features and behaviours of the ZG. The data communications between ZG stations makes use of broadcast transmission to address unknown stations, multicast to address a group of stations and unicast transmissions for direct addressing. Depending on the situation, these communication strategies support the management of the WiFi-DT, allowing search procedures i.e searching for ZGs and tier 1 nodes (based on the ZB-DT), mobility management of ZGs and addressing strategies.

Data flows in the ZG are depicted in Fig. 5. In this figure, it is possible to observe the relation between the ZG modules and procedures upon the reception of messages by the WiFi Module (Fig 5.A) NCU. The WiFi module filters these messages, selecting and executing management messages, used in Tier 2 management procedures, and relays to the Service Module (SM, Fig 5.B) the others. After verifying the standard reception conditions, the SM selects messages based on their traffic class flag. The HRT and SRT messages are relayed directly to the ZigBee Module (Fig 5.C) while the BE messages are sent to the SM proxy service that answers the request. The flows originating from Tier 1 have a similar behaviour regarding the traffic class. The BE messages are managed by to the proxy service, used for maintaining network objects image information, and the HRT and SRT are directly relayed to the NCU, that

performs protocol conversion (e.g frame formats) and dispatches messages to Tier 2.

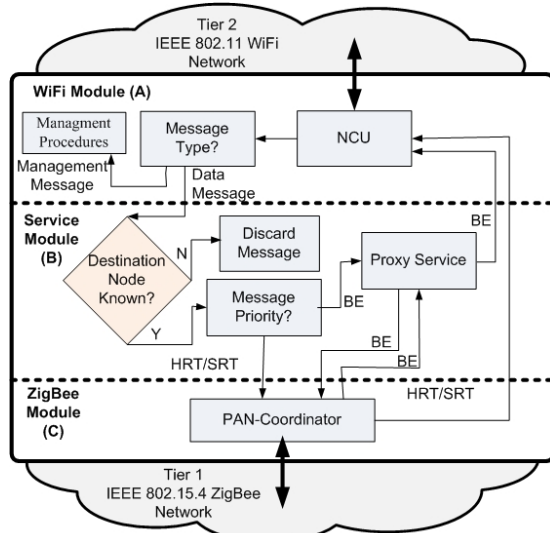


Fig. 5: ZigBee Gateway data-flow

Note that if there is any unrecoverable malfunction in the ZG that prevents its normal behaviour in critical functions (such as relaying messages though both tiers), it is necessary that the ZG automatically shuts itself down, including the ZC. Then, the WSN nodes are unable to communicate with Tier 2 so they are forced to find alternate routes. This requires the WSN restructuring so that the nodes can have a route path to Tier 2 through another ZC/ZG.

6. Ongoing Implementation Work

We are still in an early stage of the ART-WiSe architecture specification. Nevertheless, we envisage to start implementing and testing functionalities of the ZG. In this line, we are using the Crossbow Stargate [15], a single board computer equipped with a Wireless IEEE802.11b PC Card for Tier-2 network access, and a Crossbow MICAz node [16] (with ZC functionalities).

At this early stage we already have an initial version with a simple interface mechanism between the two tiers, allowing their interoperability. Regarding Tier 1, we already have a cluster-tree implementation that enables energy-efficient real-time communications [17]. Nevertheless, as stated earlier we are accessing the Tier-2 technologies that enable QoS and real-time requirements.

7. Concluding Remarks and Future Work

In this paper, we have presented ongoing work on the specification of an IEEE 802.15.4/ZigBee to IEEE 802.11 Gateway for the ART-WiSe Architecture. We strongly believe that it is possible to engineer a ZG that supports real-time constraints using COTS technology. Nevertheless, there are still many open issues, namely on

the Tier 2 technologies, protocols and mechanism. In the future, we also intend to address other issues such as: data aggregation techniques, addressing paradigms, routing protocols and deployment strategies.

8. Acknowledgement

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References

- [1] A. Koubâa, M. Alves, E. Tovar, "A Two-Tiered Architecture for Real-Time Communications in Large-Scale Wireless Sensor Networks: Research Challenges", in the WiP Session of ECRTS'05, Palma de Mallorca, Spain, 2005.
- [2] ART-Wise Framework, <http://www.hurray.isep.ipp.pt/art-wise>
- [3] IEEE 802.11, 1999 Edition (ISO/IEC 8802-11: 1999) IEEE Standards for Information Technology - Telecommunications and Information Exchange between Systems - Local and Metropolitan Area Network - Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications
- [4] IEEE 802.15.4 Standard Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), 2003. <http://standards.ieee.org/>
- [5] ZigBee Alliance, "ZigBee Specification" <http://www.zigbee.org>
- [6] IEEE 802.11e-2005, IEEE Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements, <http://standards.ieee.org/>
- [7] Intel Research, Heterogeneous Sensor Networks: Exploring Way to Improve Network Performance, <http://www.intel.com/research/exploratory/heterogeneous.html>
- [8] Meshnetics "ZigBit Ethernet Gateway", <http://www.meshnetics.com>
- [9] Arch Rock "Arch Rock Primer Pack" <http://www.archrock.com/>
- [10] O. Gnawali, B. Greenstein, K. Jang, A. Joki, J. Paek, M. Vieira, D. Estrin, R. Govindan, E. Kohler, "The TENET Architecture for Tiered Sensor Networks", In Proceedings of the ACM Conference on Embedded Networked Sensor Systems (Sensys), Boulder, Colorado, November 2006.
- [11] V. Kottapalli, A. Kiremidjiana, J. Lynch, E. Carryer, T. Kenny, K. Lawa, Y. Leia, "Two-Tiered Wireless Sensor Network Architecture for Structural Monitoring", In Proc. of 10th Annual International Symposium on Smart Structures and Materials, San Diego (USA), Mar. 2003
- [12] W. Ye, J. Heidemann, "Medium Access Control in Wireless Sensor Networks", Wireless Sensor Networks, pp. 73-91, ISBN:1-4020-7883-8, Kluwer Academic Publishers, 2004.
- [13] A. Koubâa, M. Alves, B. Nefzi, Ye-Qiong Song, "Improving the IEEE 802.15.4 Slotted CSMA/CA MAC for Time-Critical Events in Wireless Sensor Networks", 5th International Workshop on Real-Time Networks (RTN'06), Dresden, Germany, July 2006.
- [14] IEEE 802.11s, Draft 2006 "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Extended Service Set Mesh Networking", <http://standards.ieee.org/>
- [15] Crossbow Stargate REV1.2, <http://www.xbow.com>
- [16] Crossbow MICAz mote, <http://www.xbow.com>
- [17] A. Koubâa, A. Cunha, M. Alves, "A Time Division Beacon Scheduling Mechanism for IEEE 802.15.4/ZigBee Cluster-Tree Wireless Sensor Networks", in the proceedings of Euromicro Conference on Real-Time Systems (ECRTS 2007), Pisa(Italy), July 2007