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Hardware platform for wide-area vehicular sensor networks with mobile nodes

Ignacio Del Castillo, Félix Tobajas *, Roberto Esper-Chaín, Valentín De Armas

Department of Electronic Engineering and Automatic (DIEA), Institute for Applied Microelectronics (IUMA), University Of Las Palmas de Gran Canaria (ULPGC), Las Palmas de Gran Canaria, Spain

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A B S T R A C T

In recent years, Wireless Sensor Networks have experienced significant growth, mainly motivated by the development of standard communication protocols and the availability of low cost microcontrollers and wireless transceivers, resulting in low-power small-size sensing and data processing capable devices, and wireless communication links. In this paper, a hardware platform for the deployment of a heterogeneous multi-tiered Sensor Network architecture supporting highly mobile nodes covering wide geographic areas for automotive applications is proposed. In the presented network architecture, the low level system consists of an IEEE 802.15.4 based Wireless Sensor Network fully composed of compatible devices that support all the standard functionalities. As a novelty, some extensions are proposed to release part of the topological restrictions of IEEE 802.15.4 communication protocol which limit the development of WSN for applications with wide area coverage and high mobility requirements. The proposed hardware platform has been implemented and experimentally validated and characterized in vehicular applications to monitor and communicate specific environmental parameters in a heavy transport fleet.

1. Introduction

Wireless Sensor Networks (WSNs) are a useful, efficient and easy solution for data acquisition in places where using fixed and wired infrastructures presents several difficulties and disadvantages. A WSN is composed of dense, distributed autonomous nodes capable of sensing, processing and wireless communication. These wireless nodes are electronic devices characterized by being intelligent, small-sized, low in cost, battery-driven, and easy to install [1,2]. The most important advantage of WSNs consists of the easy network deployment and the high configurability, which allows developing different network structures with no significant physical changes.

Nowadays, IEEE 802.15.4 standard is the prevalent communication protocol intended for WSN. IEEE 802.15.4 standard specifies the PHYsical (PHY) and Medium Access Control (MAC) layers for low-rate Wireless Personal Area Networks (WPAN) with ubiquitous connectivity between low-cost, low-power fixed nodes [3]. In general, an IEEE 802.15.4 WSN is composed of one sink node, named *Personal Area Network* (*PAN*) *coordinator*, and set of nodes that can be *Full-Function Devices* (*FFDs*) or *Reduced-Function Devices* (*RFDs*), attending at their functionality. FFDs can communicate with any other FFD or RFD device within the WSN and fit within any supported topology, while RFDs act as sensing nodes and can only communicate with an FFD. The sink node is always a FFD.

In IEEE 802.15.4, two basic topologies are allowed, but not completely described by the standard since definition of higher layers functionalities is out of its scope. In a *star* topology (single-hop), an FFD can act as the PAN coordinator node to initiate a WPAN, being the only node allowed to form links with more than one device, while RFDs are intended to perform simple monitoring applications and transmitting collected data. The *peer-to-peer* topology (multi-hop) is mostly composed of FFDs able to form links to other devices by allowing the association of nodes to the network, acting as intermediate forwarding nodes, with the occasional inclusion of RFDs as end nodes [4]. However, the introduction of multi-hop requires nodes to implement routing tasks, and as a consequence, additional processing resources and device memory for storing routing tables [5]. IEEE 802.15.4 can also support other multi-hop network topologies, such as *tree* or *mesh*. However, these network topology options are not part of the IEEE 802.15.4 standard, but are described in the Zigbee Alliance specifications [6]. *Zigbee*, with *6LoWPAN* (*IPv6 over Low power Wireless Personal Area Networks*) [7], are the most popular standards developed to im-

* Corresponding author.
E-mail addresses: idelcastillo@iuma.ulpgc.es (I. Del Castillo), tobajas@iuma.ulpgc.es (F. Tobajas), esper@iuma.ulpgc.es (R. Esper-Chaín), armas@iuma.ulpgc.es (V. De Armas).

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plement the NetWorK (NWK) layer communication protocol based on the IEEE 802.15.4 PHY and MAC layers, in order to provide a complete solution for WSN development. All devices belonging to a particular network, regardless of the type of topology, use their unique IEEE 64-bit addresses and a short 16-bit address which is allocated by the PAN coordinator, to uniquely identify each node.

In traditional Wireless Sensor Network deployment, nodes are spread in large number in a certain geographical area, forming ad-hoc *planar Wireless Sensor Networks* to monitor and control physical or environmental parameters, or to collect data to be reported to a central node that stores and analyses the information gathered from the monitored field [8,9]. Sensory data is transferred from the source nodes to a remote sink node in a *peer-to-peer*, multi-hop, and self-organizing manner. Normally, all nodes have similar energy, storage, computing, and transmission capabilities, which means they are *homogeneous*. However, with static and fixed data access nodes, such a network architecture has many inherent problems, including uneven energy consumption among nodes, restricted scalability, area coverage and nodes mobility, low data transmission efficiency, inflexible deployment, or single network structure [10].

As a result, *hierarchical WSNs* have become a research area of interest in recent years. Unlike flat networks, hierarchical WSNs consist of heterogeneous nodes performing different sensing, processing and communication tasks, and combining several wireless technologies [11,12]. Some similar concepts, such as *multi-tier architectures* or *heterogeneous networks*, are also presented in literature [13]. Compared with *planar Wireless Sensor Networks*, hierarchical WSNs optimize network performance in terms of energy efficiency, throughput, reliability and scalability, and also extend potential application scenarios of WSN, as it is the case of networks with mobile nodes [14]. In this sense, while several works have focused on heterogeneous WSNs with mobile sink nodes collecting data transmitted from static sensors placed at fixed locations in previously formed WSN, few works have considered heterogeneous WSNs in the context where both sink and sensor nodes present a high mobility over wide areas [15–18].

In WSN, wireless communication usually dominates the energy consumption [19]. Nodes usually are equipped with microcontrollers and radio transceivers having limited resources in terms of computational power, transmission range, bandwidth and battery capacity, and use highly efficient communication protocols. Low cost microcontrollers and wireless transceivers have been a clue for very cost-effective solutions development over last years, which have led WSN into a rapid market growing, expecting to continue. The low-power requirement must therefore not only influence all aspects of node design, but also the entire heterogeneous network. Furthermore, the application strongly affects the choice of the wireless technology to be used. Once application requirements are set, the designer has to select the technology which allows satisfying these requirements. To this aim, the knowledge of the features, advantages and disadvantages of the different technologies is fundamental. Applications of WSN range from environmental control, health care, surveillance, positioning and tracking, to vehicular networks [20] or Intelligent Transportation Systems [21].

In this paper, a heterogeneous hierarchical IEEE 802.15.4 based WSN supporting highly mobile coordinator and sensor nodes covering wide geographic areas is presented. This network has been experimentally validated and characterized in vehicular applications to monitor and communicate some environmental parameters in a heavy transport fleet using a set of commercial trucks with refrigerated trailers as a test-bed. For that purpose, an automotive oriented hardware platform was developed to implement the functionality of IEEE 802.15.4 compatible nodes installed on each vehicle, including some functional extensions **of the MAC layer** proposed as a novelty to ease the deployment of wide-area mobile sensor networks.

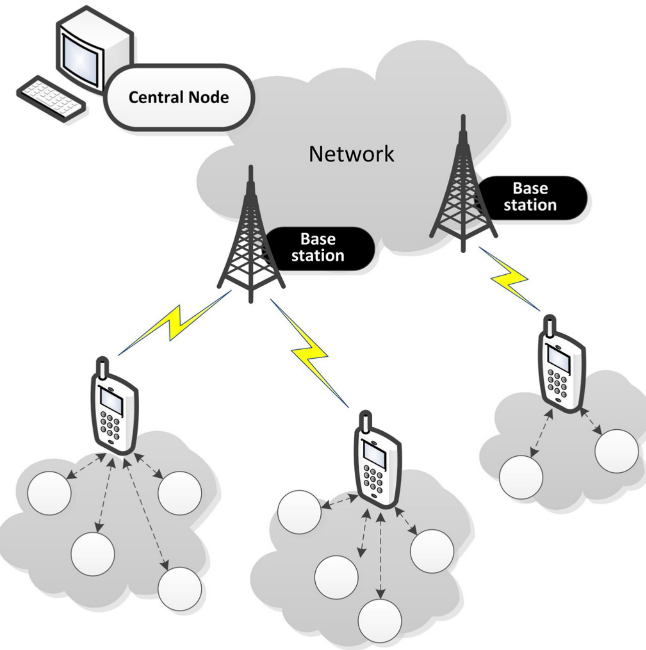

Fig. 1. Typical three-tiered sensor network architecture.

2. Hierarchical architectures for Wireless Sensor Networks

Hierarchical sensor networks combine several wireless technologies and heterogeneous devices, with nodes mainly acting as sinks responsible for gathering and forwarding data from underlying sensor nodes. Some of the devices in hierarchical WSN are able of communication with better capability, some are mobility enabled, etc. Hierarchical sensor networks are usually organized in multi-tiered architectures [22].

Combining the infrastructure-based cellular network with the infrastructure-free wireless sensor network, *three-layer architecture* makes full use of the complementary features of the two kinds of networks and solves network performance-degradation caused by fixed access points [23], so it is quite suitable for future ubiquitous, heterogeneous, cooperative networks [24]. Specifically, the cellular network provides a powerful service platform and mature operation mode, but its centralized control and management system makes it less flexible. Owing to its self-organizing feature, a WSN is quite flexible, but its transmission distance is short and it lacks a mature operation mode and management system. Integration of the two networks enables a locally-deployed WSN to acquire information via the coverage of a mobile Wide Area Network (WAN), and to transfer and exchange the data in a wider range. Mobile WAN uses the information collected by the WSN to expand its service capabilities.

The lowest layer in a WSN with three-tier architecture, as shown in Fig. 1, is a deployed WSN with sensor nodes being able to communicate with upper layer mobile agent in near range. Mobile agents are responsible for gathering sensory information from lower layer and then forwarding to upper layer. The highest layer represents generally the fixed network consisted on some specific number of Base Stations of cellular networks, which serves as the access points to the Network to forward the node sensory information to a Central Node. In typical three-tiered WSN architectures, sensor nodes don't communicate with its neighbors and don't deliver sensory information until some mobile agent come close to