IPv6 solutions enabling mobile services for the "Internet of Things"

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Abstract

In this paper we focus on wireless proximity technologies, which are attracting an ever increasing attention for advantages such as easy integration in user mobile phones and terminals, low power consumption and low chipset costs. However, interoperability between wireless proximity technologies and IP networks is at a very early stage. For instance, the ZigBee protocol stack, which is one of the most widespread protocol stack for IEEE 802.15.4 low-rate wireless personal area networks (LR-WPANs), in its current version integrates a network layer not compatible with the IP network layer. Thus in this paper, we first of all describe real application scenarios and mobile services which demonstrate how mobile phones and terminals integrating some kind of wireless proximity technology can take great advantage from the direct interoperability with IP networks. Secondly, as proof of concept, we also present a real test-bed based on a protocol architecture where IEEE 802.15.4 WPANs nodes and mobile terminals are IP-enabled and can interact with the public Internet, and describing real applications running on the test-bed[1].

1 Introduction

Wireless proximity technologies are becoming more and more attractive for services deployed on both fixed and mobile terminals, like mobile phones, PDA, home gateways and set-top boxes. Through wireless short range communication user terminals may interact with the surrounding environment and communicate with many other devices. For instance, a home gateway may provide access to the home environment, e.g. heating and air conditioning, washing machine and so on, to remotely control their status. On the other hand, a mobile terminal may locally interact with devices like vending machine, point of sale, information spot enabling services in the field of mobile advertising and commerce, info-mobility, tourism and so on. Furthermore, the communication with both environmental and body sensors enable scenarios like ambient monitor and personal healthcare. In fact, the user terminal becomes the gateway between wide area networks and the proximity environment enabling the so called Internet Of Things [1], a futuristic vision introducing the concept of a network where all the things are able to communicate with each other across the whole world.

Among wireless proximity technologies, low-rate wireless personal area networks (LR-WPANs) are receiving an ever increasing attention for their capability of supporting low-rate and low-power short range wireless communications and, as a consequence, applications with simple wireless connectivity, relaxed throughput and relaxed latency requirements in fields such as home automation, industrial control, personal medical assistance and remote control and monitoring.

In addition, LR-WPANs technologies are attractive for many reasons. They can be easily integrated in small devices, giving advantages for integration in both fixed devices and mobile user terminals. Their power consumption is low, thus not impacting on battery lifetime. The cost of chipsets are low and, as a matter of fact, these technologies are often referred to as disappearing technologies. Moreover, forming a network to have simultaneous access to different devices is a very attractive perspective.

One of the most important and currently available reference standards for LR-WPANs is IEEE 802.15.4 [2][3], which defines the physical layer and the medium access control (MAC) sub-layer. In what follows, the LR-WPANs using IEEE 802.15.4 physical and MAC layers will be denoted as IEEE 802.15.4 LR-WPANs.

The most widespread and common protocol stack for IEEE 802.15.4 LR-WPANs is probably the ZigBee protocol stack, where the network layer and the application framework defined by the ZigBee Alliance in [4] are used in conjunction with IEEE 802.15.4 at physical and MAC layers.

Although other near field technologies like NFC and Blue-

[1]This work has been carried out in cooperation with and with funding from Telecom Italia.

tooth have been already used on mobile phones, telecommunication operators are strongly considering the usage of IEEE 802.15.4 LR-WPANs and ZigBee for the above mentioned reasons. In particular, Telecom Italia, the mayor Italian operator and member of ZigBee Alliance, envisages in [5] a scenario where there are not only stand-alone ZigBee nodes, but there are also mobile phones equipped with either the so-called ZSIMs, which are SIMs integrating a ZigBee node, or the so called ZSDs, that are micro or mini SD cards integrating a ZigBee node.
Unfortunately, the network layer of the ZigBee protocol stack is not compatible with the IP network layer. On the one hand, this makes the ZigBee protocol stack the perfect solution for closed, ad hoc environments. On the other hand, the interoperability between ZigBee networks and IP networks requires complex, heavyweight and stateful gateways to establish and manage the communication and to operate network address translations. The lack of direct interoperability may be regarded as a limiting factor for the following reasons:

- it makes ZigBee networks very unsuitable for open and connected environments, that would clearly benefit from the IP support;
- it limits the evolution of ZigBee networks towards the emerging future "Internet of Things". In such a scenario, the IP protocol with its end-to-end inspiring principle appears the most natural and obvious candidate to building a global network out of things.

Thus, we aim in this paper at i) describing real application scenarios, where portable and mobile terminals, such as smart phones or PDAs, are equipped with Secure Digital (SD) cards integrating an IEEE 802.15.4 node and can take great advantage from the direct interoperability between IEEE 802.15.4 WPANs and IP networks, and ii) as proof of concept, presenting a real test-bed based on a protocol architecture where IEEE 802.15.4 WPANs nodes and mobile terminals are IP-enabled and can interact with the public Internet, and describing real applications running on the test-bed.
In doing this, we assume as starting point the solution recently proposed by the IETF 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks) working group in the RFC 4944 [6], for enabling the transmission/reception of IPv6 packets over LR-WPANs based on IEEE 802.15.4 standard. This solution consists in a sort of adaptation layer, the so said LoWPAN adaptation layer, to be included between the IEEE 802.15.4 MAC sublayer and the IPv6 layer.
The paper is organized as follows. Section 2 discusses the related work. Section 3 describes pertinent real application scenarios. Section 4 presents the protocol architecture implemented in the test-bed, while section 5 describes the implemented test-bed and the developed applications running on the test-bed. Finally, we conclude the paper in section 6.

2 Related work

In the literature we can find several solutions to interconnect ZigBee WPANs to IP networks.
TinyREST [7] uses an HTTP-based approach. It assigns a URL address to all resources, and it uses HTTP methods and extensions to request data or send command to the IEEE 802.15.4 WPANs. However, HTTP messages are not encapsulated within TCP packets, and they are transmitted via the TinyOS network stack. Since this stack is not IP-compliant, a HTTP-2-TinyREST gateway is necessary for establishing and handling the communication to/from the Internet and the IEEE 802.15.4 WPANs, including all the necessary validity checks and message format mappings.
TinySIP [8] uses the SIP protocol and a subset of SIP methods to enable the communication between IEEE 802.15.4 WPANs and the Internet. As in TinyREST, a sort of communication abstraction layer is provided in such a way that TinySIP layer can be used upon an IP-not-compliant already existing protocol stack. This implies that a TinySIP gateway, mapping SIP methods to TinySIP methods and disseminating the messages among the IEEE 802.15.4 nodes, plays a fundamental role.
An internetworking mechanism to interconnect ZigBee/802.15.4 and IPv6 networks has been proposed also in [9]. Specifically, every ZigBee node is assigned with a Global Unicast IPv6 address, and each IPv6 node is also assigned with a ZigBee short address. In addition, IPv6 nodes are organized in Multicast Groups to enable the reception of broadcast messages from ZigBee networks. The key component of the system is the gateway which i) assigns ZigBee nodes and IPv6 nodes with the corresponding IPv6/ZigBee addresses, ii) stores the pairs (ZigBee address, IPv6 address), iii) keeps trace of all the on going communications and executes all the necessary format translation operations.
The above literature proposals exploit a complex, stateful gateway between ZigBee/IEEE 802.15.4 LR-WPANs nodes and IP networks; the gateway establishes and handles the communication between the Internet and the IEEE 802.15.4 WPANs and manages all the necessary validity checks and message format translations. A completely different and more radical approach is to replace the network and upper layers of ZigBee with a TCP/IP stack, keeping only the physical and MAC layer of IEEE 802.15.4. This is the approach adopted by The IETF 6LoWPAN working group, which has recently defined an adaptation layer [6], the so-called LoWPAN adaptation layer, located between the IEEE 802.15.4 MAC layer and the IPv6 layer to enable transmission/reception of IPv6 packets over LR-WPANs based on the IEEE 802.15.4 standard.
With respect to the state of the art, the contributions of this paper are: i) to define a complete protocol architecture, based on LoWPAN adaptation layer and including functionalities such as self-configuring address assignment, multihop routing, transport mechanisms, self-configuring network and service discovery, ii) to present a real test-

bed, which demonstrates the functionality of our proposed solution and the great advantage that IEEE 802.15.4 networks can take from direct IP support. Moreover, we want to highlight that in this paper we aim at presenting a test-bed conceived for enabling real mobile services on real smart phones or PDAs, which are equipped with Secure Digital (SD) cards integrating the proposed protocol architecture. On the contrary, at SECON 2009 we presented a demonstration [10] based on a preliminary test-bed which we conceived for a development kit composed of very simple nodes equipped at most with a simple display and which we deployed to test the basic functionalities of the proposed protocol architecture (transmission/reception of IPv6 datagrams using LoWPAN adaptation layer, interconnection with the public Internet).

3 Direct IP support in real application scenarios

This section describes two application scenario that could take great advantage from the direct interoperability between IEEE 802.15.4 networks and IP networks.

3.1 “Shopping center” application scenario

In a shopping center there are different WPANs available. Such WPANs may be associated with single shops or can be administrated by the shopping center general direction. For this purpose, a pre-existing infrastructure of fixed IP-enable IEEE 802.15.4 nodes has been installed in the commercial center. Network administrator can take great advantage of the direct interoperability among the IEEE 802.15.4 WPANs available in the commercial center and the IP network. In fact, he can send configuration instructions or generic updates from a remote host/location, not directly connected to any WPAN, simply by exploiting the public Internet.

Customers of the commercial center could be equipped with portable devices, such as PDAs or smart phones, integrating a fully IP-enabled IEEE 802.15.4 node. Thanks to this, such customers can detect all the WPANs available within the commercial center, discover the offered services and select the most suitable WPAN to join. In such a way, users can receive information about product catalogues, special offers, prices, special events, etc. Such information may be sent from remote locations, through the public Internet, avoiding the need of maintaining such kind of information in devices, such as the 802.15.4 nodes, with severe constraints on memory resources. In alternative, customers associated with WPANs can receive an url, that they can access by exploiting other kind of connectivity (Wi-Fi, GPRS/UMT, etc.).

It is reasonable also to assume the possibility that customers ask their WPANs for product prices. In such a case, the PAN coordinator may ask a remote data base on the public Internet and replies to the received queries. This allows to overcome the problem of maintaining a data base, centralized and distributed, within the WPAN, that has well known limitations in the amount of data that can be stored in the associated nodes.

Finally, we can also imagine the availability of communication services, that allow customers of the commercial centers, even if in different WPANs, to exchange messages for instance in the form of chat service. In such a case, a remote server on the public Internet is responsible for management of connections/disconnections, buddy lists and message delivery among different WPANs.

3.2 “University campus” application scenario

Direct interoperability among the IEEE 802.15.4 WPANs and IP networks can also be exploited to enable a communication infrastructure aiming at providing a university campus with applications and services complementary to the basic teaching services (e.g. students communities, localization services, administrative services for students, teachers and other university personnel, welcome services for guests, etc.).

To this end, we assume the availability of a publish/subscribe infrastructure for data exchanges within WPANs and, with such assumption in mind, we present a use case, which is entitled “facility sharing”: mobile devices integrating IEEE 802.15.4 nodes exploit the above communication infrastructure in order to exchange data and agree on some kind of facility that can be traded. This use case leverages on the physical nearness among actors to provide proximity services somehow alternative to “ask to everyone you meet about a specific request” or “tell something to everybody you meet”. Indeed people can have “social” reasons to not ask by “voice” (e.g. to do not disturb during a lesson, because they are shy...), so an electronic “tam-tam” could help.

To provide an example, we now present the case in which the facility to be shared is event organization. A student would like to organize a five-a-side football match. He received confirmation only from eight people. Thus, he has to find other four/six people. He resorts to the “Event organization sharing” service offered by campus network. He fills in a suitable advertisement, that he can access through the public Internet, which specifies place, date and time of the five-a-side football match. The advertisement includes also a link to the corresponding event and participants on the Doodle web site. Thanks to the people that the student meets in its campus life, the advertisement can propagate across the campus network. This propagation can be for instance affected by user profiles of people that have subscribed to the “Event organization sharing” service. In such a way, nodes which belong to guys interested in playing football can receive the advertisement. They also receive an url containing the address of the Doodle web site page referring to the event. At this point, the “Event organization sharing” service invites the user to switch to alternative, more reliable and high rate, connectivity forms (Wi-Fi, GPRS/UMTS), and users, in a seamless and simple manner, can visit the Doodle link, find out who the other participants are and add himself to the list of participant. Periodically the student and the other interested people may check the scheduling status. When the number of participants is high enough, the student can fix the event and sends a notification to the players.

4 Implemented protocol architecture

A high level overview of the implemented protocol architecture is depicted in figure 1.
The standard IEEE 802.15.4 is used at MAC sublayer.
According to 6LoWPAN specification [6], the LoWPAN adaptation layer is located between the IEEE 802.15.4 MAC sub-layer and the IPv6 layer. Such adaptation layer may be regarded as a sequence of “header type + header fields” blocks, which, in conjunction with the IPv6 payload, are encapsulated within the payload of an IEEE 802.15.4 data frame. We implemented all the header types defined in [6]: mesh header, broadcast header, fragmentation header, compressed or not compressed IPv6 header. We refer the reader to RFC 4944 [6] for a more detailed description of 6LoWPAN solution.

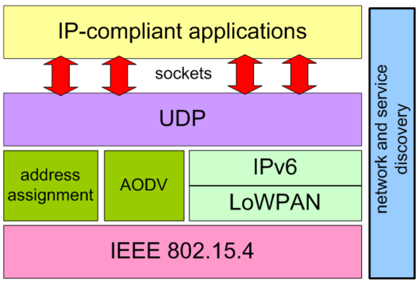

Figure 1: High level overview of the proposed protocol architecture.

The protocol stack in figure 1 includes also AODV [11] as multihop routing protocol. In fact, the 6LoWPAN IETF working group assumes that each node is equipped with a proper routing table to support multi-hop forwarding capabilities, but it does not mention how to fill such routing tables.
In addition, the protocol stack in figure 1 includes a module for the 16-bit layer 2 short address assignment. In fact, the specification of how the PAN coordinator assigns 16-bit short addresses is out of the scope of the IEEE 802.15.4 standard, which leaves the responsibility of such assignment to upper layer protocols. To this end, we included a solution based on the Duplicate Address Detection (DAD) procedure described by Perkins et al. in [12].
The availability of IPv6 at network layer allows to use any IP-compliant transport protocol (UDP, TCP, etc.). Nevertheless, due to the hardware limitations of common IEEE 802.15.4 devices, we decided to include just UDP.
The stack makes available standard socket APIs to application developers. Thus, as regards the application layer, applications may take advantage from socket APIs to interact with the underlying transport protocol.
As last functionality, the protocol stack in figure 1 includes a module for network and service discovery. In fact, according to the current IEEE 802.15.4 standard, the network discovery process exploits the transmission of beacon frames from coordinators, both in beacon-enabled mode and in non beacon-enabled mode. The information that IEEE 802.15.4 nodes can deduce from the examination of the beacon frames during the network discovery phase mainly relates to i) the (64 bit) PAN identifier of the network, ii) the logical channel occupied by the network, iii) the capability of the network to accept joining requests. As a consequence, IEEE 802.15.4 nodes can choose a network on the basis of the PAN identifier only and cannot automatically (e.g. with zero-configuration) select a network based on the offered services. Thus, IEEE 802.15.4 nodes can only exhaustively associate with all the available networks, until services of interest are discovered in one of these networks. To overcome the above limitation and enable self-configuring network discovery procedures, we propose the creation of a “default discovery WPAN”, with which each new joining node initially associates to find out information about the services offered by available WPANs. As regards how the default discovery WPAN collects information about the existing WPANs and the offered services and how a joining node interacts with the default discovery WPAN, we propose a solution based on 6LoWPAN/IPv6 gateways. These gateways are required in the interaction between IEEE 802.15.4 6LoWPAN devices and IPv6 networks in order to translate packet format in case of compression and to cope with possible fragmentation/reassembly operations, and they operate in stateless and lightweight manner since they have not to store any state information about address translations and on going communications.

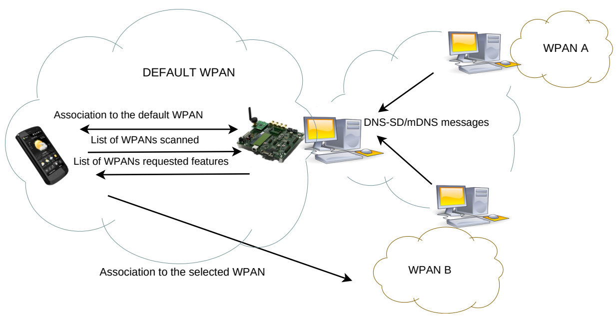

Figure 2: Interaction between 802.15.4 nodes and default discovery WPAN gateway.

As depicted in figure 2, each 6LoWPAN/IPv6 gateway announces its WPAN (WPAN identifier, service offered, IPv6 address prefix of the network) by transmitting DNS-

SD/mDNS [13] messages to a multicast group which also the gateway of the default discovery WPAN belongs to. When DNS-SD/mDNS messages with the discovery information are received by the gateway of the default discovery WPAN, a data base of available WPANs and their offered services is created. The requirements for the creation of the database in the gateway of the default WPAN is that both WPAN gateways and default WPAN gateway are associated with the same multicast group to send and receive DNS-SD/mDNS messages. A new joining IEEE 802.15.4 6LoWPAN device i) uses the IEEE 802.15.4 facilities for channel scanning and finds out the WPANs available in its neighborhood, ii) joins the default discovery WPAN and queries the 6LoWPAN/IPv6 gateway about the discovered WPANs, iii) selects a suitable WPAN based on the offered services.

Finally, figure 3 depicts a high level overview of the architecture of a 6loWPAN/IPv6 gateway. As it can be seen, a 6loWPAN/IPv6 gateway may be regarded as the union of two separate components: the 802.15.4 node and the IPv6 node, connected through a serial line. The architecture of the 802.15.4 node is almost identical to the one presented in figure 1, with the only exception of a special module for decompression/compression of packet format and and a special module for the transmission/reception of packets to/from the serial line. The IPv6 node plays instead the twofold role of i) forwarding the packets received through the serial line toward the public Internet and viceversa and ii) providing the previously described network and service discovery functionalities. This also means that the 6LoWPAN/IPv6 gateway does not perform NAT-typical operations and can operate in stateless manner.

5 Implemented real test-bed

The protocol architecture presented in section 4 has been implemented in a real test-bed.

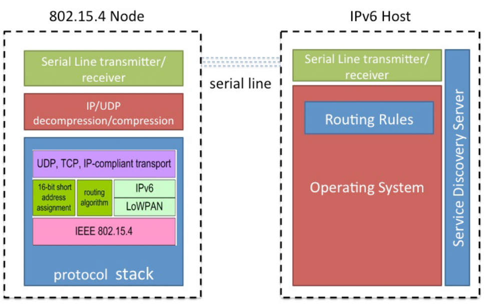

Figure 3: High level overview of a 6loWPAN/IPv6 gateway protocol architecture.

As regards the test-bed hardware, we used common PDAs (running Windows Mobile 5.0 or PocketPc 2003) equipped with Secure Digital Input/Output (SD) cards able to run the proposed protocol stack in a firmware. For development purposes, we also used the Texas Instruments' CC2430ZDK [14] development kit. This is based on the CC2430 System-on-Chip, which basically includes the 2.4 GHz IEEE 802.15.4 transceiver, an 8051 microcontroller and the flash memory. The kit includes three simple minimal board (CC2430DB) and two evaluation boards (CC2430EB) equipped with joystick, several buttons, USB port, RS-232 port and LCD display. The RS-232 port has been used to connect an evaluation board to the Linux box and to implement the 6LoWPAN/IPv6 gateway. We used, instead, common off-the-shelf hardware for the Linux box.

As depicted in figure 4, in order to enable the interaction between the SD card and the applications on the PDA, we developed an API inspired by the famous Berkley socket: using this API the application developer can simply reuse/adapt existing applications or develop from scratch IP-enabled applications with minor effort. More precisely, we implemented an application that interacts with the firmware loaded on the SD cards and allows users i) to visualize on the PDA display the available WPANs and information about the offered serveices, ii) to chat with other users, even if connected to different WPANs, iii) receive advertisement messages.

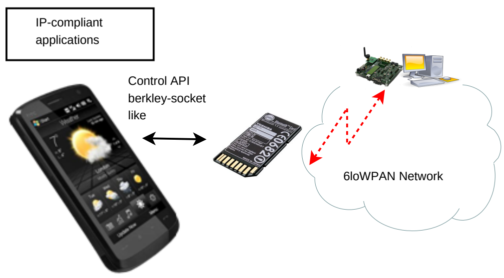

Figure 4: Interaction between the mobile node and the 6loWPAN-enabled SD.

We conceived the following application scenario. In a shopping center there are two different IEEE 802.15.4 LR-WPANs and a default discovery WPAN. Such a scenario is depicted in figure 5. WPAN1 and WPAN2 denote the two WPANs in the shopping centers, and G1 and G2 denote the corresponding IPv6/6LoWPAN gateways. The default discovery WPAN makes possible the network and service discovery, when a PDA wants to join a WPAN, and operates as described in subsection 4. As regards the chat function, we developed a single room client-server chat. The remote chat server depicted in figure 5 manages user connections and disconnections, buddy lists, and it allows buddy users to discover each other. In addition, in case of users connected to different WPANs, the chat server makes possible the communication by receiving messages from the IPv6/6LoWPAN gateway of the source WPAN and forwarding messages to the IPv6/6LoWPAN gateway of the destination WPAN. As regards the advertisement server, it interacts with the IPv6/6LoWPAN gateways to send advertisements and promotional messages, that PDAs receive in form of pop-up messages. These messages can also contain URLs that users can access through the default web browser by using the GSM/UMTS and/or Wi-Fi connectivity.

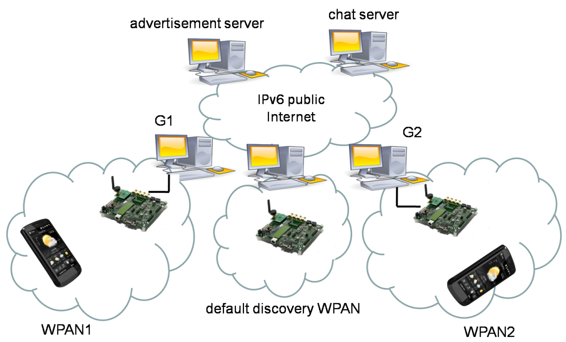

Figure 5: Reference application scenario.

The above application was developed for Windows Mobile 5.0 and PocketPc 2003, and it is based on Microsoft Foundation Classes (MFCs). Figure 6 shows three screenshots of the test-bed applications.

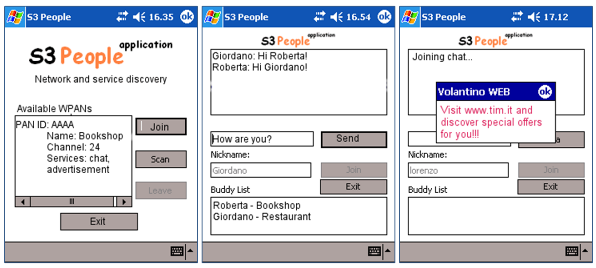

Figure 6: Screenshots of the GUI of the developed application.

6 Conclusions

In this paper we describe real application scenarios where mobile terminals integrating IEEE 802.15.4 nodes can take great advantage from direct and native IP support. We also present both a protocol architecture that allows IEEE 802.15.4 nodes to fully and directly inter-operate with IP networks and a real test-bed, which has been conceived for fully IP-enabled IEEE 802.15.4 nodes and is able to support the proposed real application scenarios. As future work, we will assume the availability of a publish/subscribe infrastructure for data exchanges and, with such reference application scenario in mind, we will investigate and design an innovative routing mechanism, which integrates both Mobile Ad-hoc NETworks (MANETs) and Delay Tolerant Networks (DTNs) routing functionalities and which will solve the issue of IEEE 802.15.4 nodes going temporarily down during the sleeping mode.

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