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On the Use of IEEE Std. 802.15.4 to Enable Wireless Sensor Networks in Building Automation

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IEEE 802.15.4 is a new standard that addresses the need of low-rate wireless personal area networks or LR-WPAN with a focus on enabling pervasive wireless sensor networks for residential, commercial and industrial applications. The standard is characterized by maintaining a high level of simplicity, allowing for low cost and low power implementations. This paper presents a brief technical introduction of the IEEE 802.15.4 standard and analyzes its applicability for building automation applications.

KEY WORDS: Wireless sensor networks; building automation; ad hoc networks; low-rate wireless; personal area networks; IEEE 802.15.4

1. INTRODUCTION

With the success of wireless local area networks (WLANs), the wireless networking community has been focused in finding new avenues to enable wireless connectivity to existing and new applications involving machine-to-machine communications. Recently, the concept of a standardized low rate wireless personal area network (LR-WPANs) has emerged [1–5], fuelled by the need to enable inexpensive wireless sensor networks enabling monitoring and control of non-critical functions in the area residential, commercial and industrial applications. In December 2000 Task Group 4, under the IEEE 802 Working Group 15, was formed to begin the development of a LR-WPAN standard. The goal of Task Group 4 was to provide a standard with the characteristics of ultra-low complexity, low-cost and extremely low power for wireless connectivity among inexpensive, fixed, portable and moving devices [1]. The effort concluded in October 2003 with the ratification by the IEEE Standards Association of the IEEE Std. 802.15.4 [5].

The primary focus of building automation is the reduction of energy consumption in the building installations through automated mechanisms to lower total energy costs and comply with governmental regulations. Building automation comprises a set of diverse functions that includes energy conservation, environment control, lighting control, safety and security. All of this functionality can be overlaid in a common communications network since the characteristics of each of these functions require similar performance requirements.

The interest in using wireless sensor networking in building automation applications is based on the need to lower installation cost which comes in the form of cabling, labor, materials, testing, and verification. For example, the installation cost of a light switch in a building facility can be as high as 10–30 times the cost of the switch; this estimate does not includes the possibility of additional work such as conduit installation and infrastructure work. Furthermore, the installation cost of a large number of existing building facilities can be prohibited high due to the existence of pollution agents such as asbestos; in this case, wireless sensor networks and power line carrier are the only solution viable for retrofitting buildings with business automation machinery. Low-cost power line carrier still shows serious reliability issues that limit the use of the technology.

Section 2 of this paper presents a technical overview of the IEEE 802.15.4 standard. Section 3,

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presents the motivation for the use of wireless sensor networking in building automation applications based on IEEE Std. 802.15.4, followed by Section 4 where challenges in the deployment of these networks are identified. Conclusions are presented in Section 4.

2. TECHNICAL OVERVIEW

A summary of the high-level features of the IEEE 802.15.4 is shown in Table 1.

By favoring low-cost and low power, IEEE 802.15.4 is enabling applications in the fields of industrial, agricultural, vehicular, residential and medical sensors and actuators. Until recently, these applications could not make use of current wireless technologies or would have to use proprietary solutions (in most cases unidirectional) [2, 3, 5].

The intent of IEEE 802.15.4 is to address applications where existing WPAN solutions are too expensive and the performance of a technology such as Bluetooth^{TM} is not required. IEEE 802.15.4 LR-WPANs complement other WPAN technologies by providing very low power consumption capabilities at very low cost, thus enabling applications that were previously impractical. Table 2 illustrates a basic comparison between IEEE 802.15.4 and other IEEE 802 wireless networking standards. The power consumption of first generation IEEE 802.15.4 devices is near 50% lower than those from Bluetooth-enabled technologies. It is expected that the next generation will be as low as 10 times lower power consumption.

The IEEE 802.15.4 standard was designed to be used in a wide variety of applications with simple wireless communications requirements over short-range distances, limited power, and relaxed throughput needs. IEEE 802.15.4 facilitates Wireless Sensor Networks (WSNs) with the goal of reducing the installation cost of sensors and actuators while enabling sensor-rich environments.

Table 2. IEEE 802.15.4 high level PHY characteristics

	802.11b WLAN	802.15.1 WPAN	802.15.4 LR-WPAN
Range	~100 m	~10–100 m	10 m
Raw data rate	11 Mbps	1 Mbps	≤ 0.25 Mbps
Power consumption	medium	low	ultra low

2.1. LR-WPAN design

A main design consideration for LR-WPANs is low power consumption, thereby maximizing battery life. To achieve low average power consumption, IEEE 802.15.4 assumes that the amount of data transmitted is short and that it is transmitted infrequently in order to keep a low duty-cycle. In addition, the packet structure was designed to add minimal overhead over the transported payload.

The standard allows the formation of two possible network topologies: the star topology or the peer-to-peer topology (see Figure 1).

In the star topology, the communication is performed between network devices and a single central controller, called the PAN coordinator. A network device is either the initiation point or the termination point for network communications. The PAN coordinator is in charge of managing all the star PAN functionality. In the peer-to-peer topology, every network device can communicate with any other within its range. This topology also contains a PAN coordinator, which acts as the root of the network. Peer-to-peer topology allows more complex network formations to be implemented; e.g. ad hoc and self-configuring networks. The routing mechanisms required for multi-hopping are part of the network layer and are therefore, not in the scope of IEEE 802.15.4.

The IEEE 802 project [6] divides the DLL into two sublayers, the MAC and logical link control (LLC) sublayer. The LLC is standardized in 802.2 [7] and is common among the 802 standards such as

Table 1. IEEE 802.15.4 High level characteristics

Frequency band	Two PHYs	Low-band (BPSK)	868 MHZ	1 channel–20 kb/s
			915 MHZ	10 channels–40 kb/s
		High-band (O-QPSK)	2.4 MHZ	16 channels–250 kb/s
Channel access	CSMA-CA and slotted CSMA-CA			
Range	10 to 20 m			
Addressing	Short allocated 16 bit or 64-bit IEEE			

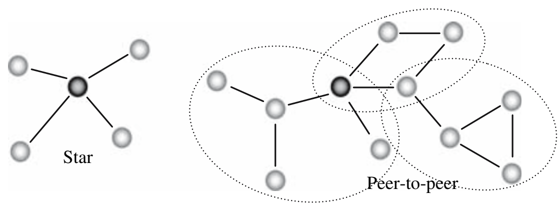

Fig. 1. IEEE 802.15.4 network topologies.

802.3, 802.11, and 802.15.1, while the MAC sublayer is specific to the physical layer implementation.

An IEEE 802.15.4 LR-WPAN device is composed of a physical (PHY) layer and a medium access control (MAC) sublayer that provides access to the physical channel for all types of transfer and ensures the reliable transfer of frames. The IEEE 802.15.4 MAC provides services to the IEEE 802.2 type I LLC through the service-specific convergence sublayer (SSCS). In addition the MAC services can be accessed through a proprietary LLC directly without going through the SSCS, enabling the use of more complex network topologies as mentioned above.

Figure 2 shows how IEEE 802.15.4 fits into the International Organization for Standardization (ISO) open systems interconnection (OSI) reference model [8].

2.2. PHY layer

IEEE 802.15.4 was designed to support two PHY options based on direct sequence spread spectrum (DSSS); this characteristic allows the use of low-cost digital IC realizations. Both PHYs make use of the same basic packet structure for low-duty-cycle low-power operation. The primary difference between the two PHYs is the frequency band. The 868/915 MHz PHY (also called low-band) is specified for operation in the 868 MHz band in Europe offering one channel with a raw data rate of 20 kb/s and the 915 MHz ISM band in North America offering 10 channels with a raw data rate of 40 kb/s. The low-band uses binary phase shift key (BPSK) modulation.

The 2.4 GHz PHY (also called high-band) specifies operation in the 2.4 GHz ISM band, with nearly worldwide availability. This band spans from 2.4 to 2.483 GHz and offers 16 channels with channel spacing of 5 MHz, operating with a raw data rate of 250 kb/s using offset quadrature phase shift key (O-QPSK) modulation. Figure 3 illustrates the IEEE 802.15.4 channel structure.

The IEEE 802.15.4 standard specifies a receiver sensitivity of −85 dBm for the 2.4 GHz band and −92 dBm for the 868/915 MHz band. Practical implementations are expected to improve this requirement. The standard specifies a transmit power capability of 1 mW, although it can vary within governmental regulatory bounds.

Both PHY layers use a common packet structure, enabling the definition of a common MAC interface. Each packet, or PHY protocol data unit (PPDU), contains a preamble, a start of packet delimiter, a packet length, and a payload field, or PHY service data unit (PSDU). The 32-bit preamble is designed for acquisition of symbol and chip timing. The IEEE 802.15.4 payload length can vary from 2 to 127 bytes. This structure is shown in Figure 4.

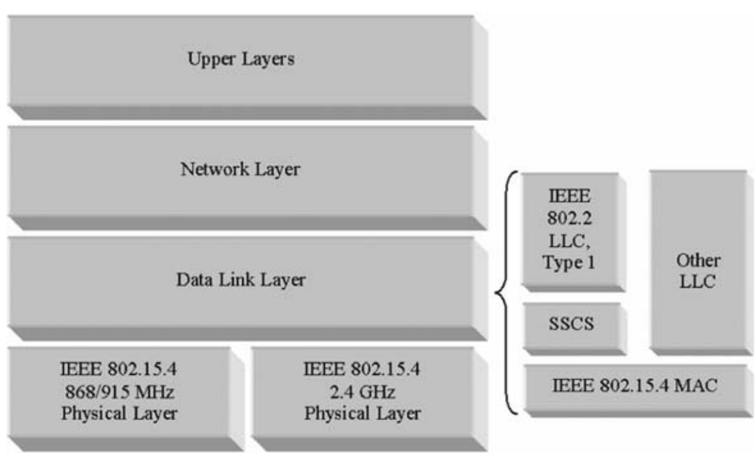

Fig. 2. IEEE 802.15.4 in the ISO-OSI layered network model.

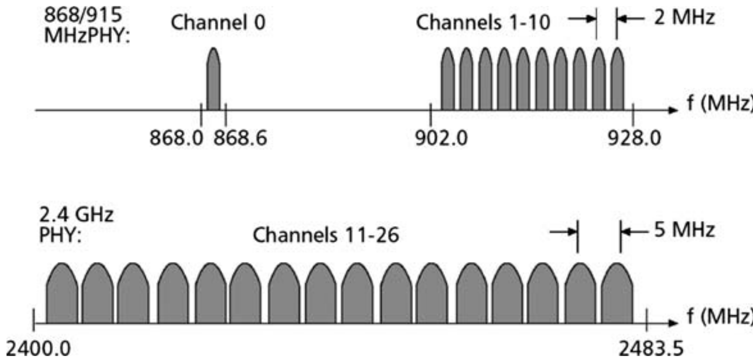

Fig. 3. IEEE 802.15.4 in the ISO-OSI layered network model .

PHY protocol data unit (PPDU)			
Preamble	Start of packet delimiter	Length Field	PHY layer payload PHY service data unit (PSDU)
4 bytes	1 byte	1 byte	2-127 bytes

Fig. 4. IEEE 802.15.4 packet structure.

2.3. MAC sublayer

The IEEE 802.15.4 medium access control (MAC) sublayer controls the access to the radio channel employing the CSMA-CA mechanism. If upper layers detect that the communications throughput has been degraded below a determined threshold, the MAC will be instructed to perform an energy detection scan through the available channels. Based on the detected energy, the upper layers will switch to the channel with the lowest energy. The IEEE 802.15.4 performs the energy scan by the use of a clear channel assessment procedure. This can be performed by following either a simple in-band energy detection above a threshold, an IEEE 802.15.4 carrier detection or a combination of both.

The 802.15.4 MAC is also responsible for flow control via acknowledged frame delivery, frame validations as well as maintaining network synchronization, controlling the association, administering device security and scheming the guaranteed time slot mechanism.

The MAC sublayer provides two services to higher layers: the MAC data service accessed through the MAC common part sublayer (MCPS-SAP) containing three primitives and the MAC management service accessed through the MAC layer management entity (MLME-SAP) containing 15 primitives.

The LR-WPAN standard allows the optional use of a superframe structure for applications requiring dedicated bandwidth to guarantee communication latency. The format of the superframe is defined by the PAN coordinator, by using the network beacons that bound the superframe structure. The superframe is composed of 16 equally sized time slots grouped in two sections: the contention access period (CAP) and the contention free period (CFP). The time slots assigned for the CFP are called guaranteed time slots (GTS) and are administered by the PAN coordinator. A pictorial of the superframe structure is shown in Figure 5.

3. ENHANCING BUILDING AUTOMATION WITH WIRELESS SENSOR NETWORKS

Typical sensors and actuators used in building control applications include light switches, dimming switches, lamps, ballasts, thermostat, vent control, and diverse sensors for light, motion detection, gas presence (smoke, carbon monoxide and others), intrusion, status, alarm and so on.

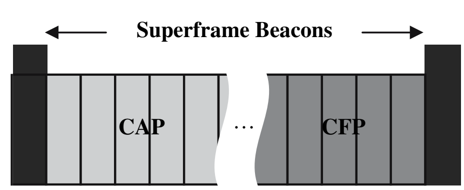

Fig. 5. Superframe structure.

Heating, ventilation and air conditioning (HVAC) and lighting systems comprises the major bulk of energy consumption in a typical commercial building, hence the focus to have a variety of sensors centered in feeding information to a central control system. Devices such as motion sensors (to determine presence of people in a room), and temperature sensors help to adequately control the HVAC system and light sensors to determine the illumination needs in a given area. In addition, there are a number of actuators that provide the control signals to ballast and relays for the lighting system and the HVAC controller to exercise the appropriate control action.

The components just described share the characteristics of relaxed throughput requirements, require low power consumption for ubiquitous deployment of battery powered sensors and the need the use of low cost communications links able to form scalable networks since the networking topology of buildings have a great 'architectural' variability. These features make the building automation application an excellent candidate for the use of IEEE Std. 802.15.4 technology. Furthermore the use of ad-hoc network layers such as the one proposed in the ZigBee Alliance [9] and several others of similar non-complex nature, enables the creation of self-configuring mesh networks which makes the use of wireless sensor networking more appealing i.e. value-added ease of installation.

4. CHALLENGES IN THE DEPLOYMENT OF WIRELESS SENSOR NETWORKS IN BUILDING AUTOMATION

Even with the use of IEEE 802.15.4, the introduction of wireless sensor technologies in the building automation arena carries several implementation challenges:

4.1. Network topology

As mentioned before, IEEE 802.15.4 provides the features necessary for allowing the formation of ad-hoc network layers with multihop capability. The field of ad-hoc self-configuring networks is relatively new and no existing ad hoc network layer is able to cope effectively with the triple constraint of low-cost implementation (low complexity in hardware resources), latency control and power consumption for all wireless sensor network applications. Fortunately, lighting control in building automation applications can tolerate longer latencies than residential applications and with the few exceptions (notably switches and temperature sensors), most of the network devices in the building automation application have access to power.

4.2. Power consumption

Building automation applications cannot tolerate the use of sensor devices that require frequent (if any) battery replacement; the need for sensor maintenance goes against the low-cost requirement. Although IEEE 802.15.4 was designed to minimize power consumption while the radio transceiver is active, battery operated network devices require the use of duty-cycled operation in the order of 1% in order to achieve a battery life in the range of 2–5 years [2, 3, 5]. This in turn poses challenges in the ad-hoc network methodology (not part of the 802.15.4 standard) to maintain synchronization under the application's latency requirements.

4.3. Range

Governmental regulations put limits the RF power output. Wireless sensor networks operating in unlicensed bands deliver RF power outputs ranging from 0 dBm to 20 dBm. The limited power establishes a limited connectivity range, that is, the maximum distance between a transmitter-receiver pair is constrained. In the context of IEEE 802.15.4, the multihop capability of the relying network layer addresses this limitation.

4.4. Coexistence issues

The IEEE 802.15.4 devices can operate in either the 868/915 MHz unlicensed (UL) band or in the 2.4 GHz industrial, scientific and medical (ISM) band. The latter one is the same operational band used by other IEEE 802 wireless devices, such as IEEE 802.11b (WLAN) and IEEE 802.15.1 (Bluetooth). IEEE 802.15.4 and IEEE 802.11b standards support complimentary applications; e.g., IEEE 802.15.4 devices used to support a wireless sensor array within a building could be collocated with IEEE 802.11b in order to provide a WLAN backbone. Wireless devices based on these two standards are likely to be collocated and therefore their ability to coexist needs to be characterized in a way to determine the operational conditions that will degrade the overall network performance [10, 11].

4.5. Wireless security

The broadcast nature of wireless communication messages makes the wireless medium intrinsically insecure due to the possibility of eavesdropping, denial of service attacks, middleman intrusion and other types of attacks to the network. Although IEEE 802.15.4 implements high levels of security through the use of the AES algorithm with keys of up to 128 bits [12], the security architecture running on the upper protocol layers (network layer up to the application layer) needs to ensure secured key management and appropriate message integrity, confidentiality, and source authentication methodologies. Furthermore, the selection of the right security level for the particular building automation application is of utmost importance in the performance of the wireless network; the higher the security wrapper the longer the message length with direct implications in radio power consumption (both in the transmitting and receiving side) with direct impact in the overall network latency [13].

Organizations such as the ZigBee Alliance (http://www.zigbee.org) and the Wireless Industrial Network Alliance (http://www.wina.org) are actively working in the creation of methodologies that will allow wireless sensor networks to mitigate the issues just listed in an effort to push toward the acceleration of the use of wireless sensor networking in the commercial and industrial applications.

5. CONCLUSIONS

IEEE 802.15.4 is a new standard designed to address the needs of a variety of residential, commercial and industrial applications by enabling pervasive wireless sensor networks. The standard is characterized by maintaining a high level of simplicity, allowing low cost and low power implementations. The high level characteristics of building automation applications makes IEEE 802.15.4 a candidate technology to enable the use of low-cost wireless sensor networks with the goal of minimizing the energy consumption in building applications.

Current wired solutions in building automation applications are not scalable or not applicable to old buildings due to the presence of indoor pollution agents such as asbestos. In addition, other technologies such as power line carrier suffer of reliability issues and high cost that limits its wire spread deployment. Low-cost wireless networking solution enabled with IEEE 802.15.4 offers the capabilities required for the building application space but network architecture issues needs to be addressed in the upper layers of the protocol stack, particularly, in the ad-hoc, self-configuring network layer, security and power consumption control. Further efforts are needed in this area in order to deliver a complete solution for building automation applications.

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