A Priority-Based CSMA/CA Mechanism to Support Deadline-Aware Scheduling in Home Automation Applications Using IEEE 802.15.4

Mario Collotta, Gianfranco Scatà, and Giovanni Pau

Facoltà di Ingegneria, Architettura e delle Scienze Motorie, Università degli Studi di Enna—Kore Cittadella Universitaria, 94100 Enna, Italy

Correspondence should be addressed to Gianfranco Scatà; gianfranco.scata@unikore.it

Received 11 January 2013; Accepted 22 April 2013

1. Introduction

In order to provide a detailed introduction to the issue, this section will be divided into three subsections. Section 1.1 specifically deals with wireless sensor networks for home automation systems, explaining the reasons which led to the choice of the IEEE 802.15.4 protocol. In Section 1.2, a general overview of the IEEE 802.15.4 protocol will be shown, placing emphasis on how it supports real-time communication using the guaranteed time slots mechanism. Finally, Section 1.3 will discuss the main motivations and aims of this research work.

1.1. Wireless Sensor Networks in Home Automation Systems. Wireless sensor networks are widely used in several application areas including data processing [1], industry [2–5] home automation [6–8], and road monitoring [9, 10] thanks to several characteristics like flexibility, adaptability, and scalability [11]. An automated house is the integration of embedded devices with other nonautomated systems such as lighting, heating, and air conditioning in order to realize smart applications for home control. The main aim of this integration is to provide greater comfort, safety, optimizing and the energy consumption. Wireless sensor networks are fundamental in home automation applications whose main requirements are quality of service (QoS) and real-time constraints satisfaction [12]. Most of the domotic systems, currently available on the market, use wired networks through different communication protocols like Ethernet [13], X-10 [14], Modbus [15], or Powerline [16]. Although their functionality and reliability have been proven over the years, some important disadvantages must be considered. For example, Powerline and X-10 use the existing power line but suffer of high error rates on poor quality lines affected by noise. Modbus and Ethernet require cables for both power and data transmission. This can be expensive in terms of implementation and maintenance costs as well as being aesthetically not very functional. WSNs represent the obvious solution to these problems because they consist of several low cost and low power devices. There are several protocols available for sensor networks like Bluetooth and
IEEE 802.15.4 [17]. Through Bluetooth it is possible to connect up to seven active devices for each piconet and it uses frequency hopping (FH) and time division multiplexing (TDM) in order to regulate transmissions. Moreover, it is characterized by high power consumption. As a consequence, the IEEE 802.15.4 standard protocol is more appropriate for home automation applications.

1.2. The IEEE 802.15.4 Protocol. The IEEE 802.15.4 standard provides the physical (PHY) layer and medium access control (MAC) sublayer specifications for low data rate (up to 250 kbps in ISM frequencies, 2.4 GHz) wireless connectivity. According to the IEEE 802.15.4 standard protocol, a wireless sensor network can optionally operate in beacon-enabled mode (the more suitable for real-time traffic flows management). In this case, the time axis is divided into a sequence of superframes, each one delimited by special signaling packets (beacons). The beacons are transmitted by the PAN coordinator and are responsible for the synchronization of all network devices. In this operating mode, the superframe is divided into time slots and contains a contention access period (CAP) in which the multiple accesses to the channel are managed through the CSMA/CA algorithm. The superframe also provides a contention free period (CFP), in which certain stations can obtain access to the medium without collisions (in FIFO order) in special guaranteed time slots (GTSs), and an inactive period in which the radio interface can be put in a low energy consumption status in order to improve energy savings. Figure 1 shows the IEEE 802.15.4 superframe structure.

1.3. Motivations and Main Aim. The use of wireless technologies in home automation networks needs the study and the implementation of new scheduling and QoS [18, 19] management mechanisms in order to meet real-time constraints. In fact, considering the IEEE 802.15.4 protocol, in contention access period the access to the medium is variable and unpredictable due to the backoff mechanism. In this work, we propose an approach based on the combined use of rate monotonic (RM) [20], for GTSs allocation in the contention free period, and a variation of the CSMA/CA algorithm for channel accesses management in the CAP based on traffic flows classification. The proposed approach can help in the development of home automation applications characterized, as known, by soft real-time constraints. The main aim of this work is to reduce the waiting time during access attempts to the radio channel of embedded devices improving, at the same time, network performance of home automated environments. Results, obtained through several measurement campaigns, show how differentiating traffic flows makes it possible to effectively improve performance in terms of throughput/workload (Th/Wl) on each embedded device and, in general, on the whole network. The paper is organized as follows. Section 2 reports the main literature works about approaches to improve IEEE 802.15.4 networks performance. Section 3 shows the considered network architecture, the proposed approach, and a probabilistic analysis about relationship between network throughput and the probability of each node to find the radio channel free. Section 4 proposes a test-bed scenario showing obtained results, while Section 5 summarizes the paper reporting conclusions.

2. Related Works

The IEEE 802.15.4 wireless sensor networks have been studied by researchers which evaluated several aspects. In order to cover the main issues, the related works section has been organized by topic areas. Our main aim is to take stock of the current situation about the various aspects of the issue object of this work and then to propose our improvements.

2.1. Home Automation Networks Applications Based on the IEEE 802.15.4 Standard Protocol. In the literature, there are several works focused on home and building automation, and many of them use the IEEE 802.15.4 standard protocol for wireless connectivty of sensor nodes. In [21], the deployment of wireless sensor networks and wireless systems applied to home and building automation systems is analyzed. Authors propose an in-house deterministic code based on 3D ray launching in order to analyze the effect of the indoor topology and morphology in the operation of wireless links within different realistic scenarios. Several simulations were performed in order to obtain performance parameters, such as RSSI (received signal strength indication) and PER (packet error rate). Simulation results show that the analysis of the topology of the wireless sensor network has a strong impact on complex indoor scenarios. The use of adequate radio-planning strategies, through the application of deterministic techniques in the planning phase, leads to optimal wireless network deployments in terms of capacity, quality of service, and energy consumption. The purpose of [22] is to
demonstrate the use of IEEE 802.15.4 to provide real-time environmental information to a smart home simulator. In this work, the simulator itself and a brief technical introduction of the IEEE 802.15.4 standard are presented. Moreover, the authors analyze the reliability of IEEE 802.15.4 in a real home automation application. In fact, authors came to the conclusion that the IEEE 802.15.4 standard is very reliable and easy to implement in home wireless network scenarios thanks to the versatility and scalability of the protocol. In addition, an analysis on exposure levels to electromagnetic fields is provided. Using the IEEE 802.15.4 protocol, the exposure levels of electromagnetic radiation are very low, about 600 times lower than an ordinary cell phone. The authors of [23] describe the IEEE 802.15.4/ZigBee communication protocol, and they present its potential deployment in smart home environments. Some examples of prototype applications, in home security and automation using a ZigBee-based wireless sensor network, are presented. The authors made a comparison between the designed ZigBee-based wireless smart home system and other existing systems in market. A careful analysis on wireless architecture shows that sensors and communication devices, used for the deployment in smart home, are not required to have a high speed in communication capacities. The authors show how using the ZigBee network technology, as wireless communication standard, makes it possible to satisfy home automation networks requirements, because IEEE 802.15.4 allows to obtain robust mesh networks and complete interoperability. Instead, more studies are needed to limit the energy consumptions of devices, to improve the network scheduling mechanism, and to validate the coexistence of multiple protocols.

2.2. Energy Saving IEEE 802.15.4 Applications in Home Automation Networks. The need of smart energy management in home environments, for sustainable energy efficiency and monetary savings, is analyzed in several works. The authors of [24] provide a comprehensive summary of the state of the art in home area communications and networking technologies for energy management. The analysis shows that there are several wireless standards for home area networks, including IEEE 802.15.4, and, accordingly, the system designers choose the wireless technology that best fits their application. Moreover, the authors point out on the challenges dealing with the design of energy management systems, in terms of accuracy, compatibility, low power cost, and integration, in order to provide the guidelines for standardized and more user-friendly smart energy home automation systems. Energy management is also examined in [25]. This work introduces a novel home-energy control system design, based on ZigBee devices, that provides intelligent services for users. The authors implement the proposed system and demonstrate its potentiality using a real test bed. After an accurate analysis, the paper clearly shows that smart home control systems can provide significant cost savings in home environment applications. In this work, a specific dissertation about lighting energy reduction is done. In fact, by using an automated control system it could be possible to turn lights off based on several factors such as available daylight or time of day. Therefore, the use of wireless connections rather than wired networks involves several benefits in terms of flexibility and money savings. In order to meet home automation networks requirements, several aspects of the IEEE 802.15.4 medium access control (MAC) in contention access period (CAP), contention free period (CFP), and the overall cross period, respectively, are analyzed in [26]. An extensive discussion focuses on a variety of adaptive real-time protocols based on IEEE 802.15.4 and on many problems of wireless networks like high latency, system complexity, implementation overhead, and, mainly, great energy consumption. The authors come to the conclusion that the requirements of all aspects usually cannot be satisfied simultaneously. However, the network efficiency can be significantly improved optimizing the original specifications and dynamically adjusting the IEEE 802.15.4 protocol parameters. A home automation network architecture for energy management inside smart grid environments is presented in [27]. In order to achieve smart grid potential, the authors aim to resolve the problem of interoperability among different communications technologies deployed in the grid. The authors propose a framework for end-to-end interoperability in home and building area networks. This framework includes the 6LoWPAN protocol in order to simplify the use of IPv6 and ZigBee application profiles. The authors also focus on other issues, including interference mitigation and load scheduling, and they propose a solution to them. They propose a priority contention algorithm for high priority messages management, while, at the same time, the proposed approach uses a compression and scheduling mechanism in order to increase the efficiency of transferred data. Moreover, a frequency-agility-based interference mitigation algorithm is proposed in order to guarantee the performance of network protocols coexistence.

2.3. GTS Mechanism in Home Automation Networks. Wireless technologies in home automation applications need the development of new scheduling mechanisms in order to meet real-time constraints. A scheduling scheme, whose main aim is to obtain optimal parameters regarding the IEEE 802.15.4 frame and subframes in home automation networks, is presented in [28]. The proposed approach uses guaranteed time slots (GTSs) for transmission of real-time periodic traffic flows, since they can guarantee time constraints using the periodic delivery of beacon frames as provided by the IEEE 802.15.4 protocol. The authors consider a set of nodes requirements in an IEEE 802.15.4 network in order to define the beacon interval considering the required periods and the duty cycles. Moreover, the active subframe duration is chosen according to required bandwidths and to ensure energy saving. The authors show results in terms of throughput for different frame and subframes lengths. Numerical results show that frame and subframe duration and GTSs's schedule can be determined in order to ensure an efficient use of the network resources. Several works on the GTS aim at increasing utilization and reducing the waste of bandwidth. Anyhow, using IEEE 802.15.4 standard protocol, the GTS does not guarantee the reliable transmission in multihop networks. For this reason, GTS mechanism is also analyzed in
[29] where authors propose and implement a multihop GTS mechanism for reliable transmission in multihop networks. After a discussion on the reliable transmission in multihop networks, the authors present simulations results. In fact, several simulations have been carried out through NS-2 simulator, and results show that low end-to-end delay and high delivery ratio can be checked. Therefore, thanks to these features, the proposed mechanism is especially suitable for delivering time-sensitive data. In [30], a preliminary solution for the transmission of real-time time-triggered traffic over the IEEE 802.15.4 standard in a home automation environment with real-time requirements is shown. Authors define the design solutions focusing on GTSs transmission and reception for time-triggered traffic with real-time requirements. The proposed approach can be useful for infrastructure-to-vehicle and vehicle-to-vehicle communications and home automation applications supporting life monitoring. The authors focus their future works in peer-to-peer topology because, in this case, a device can communicate with any other device and, furthermore, several coordinators may exist. The peer-to-peer topology has the advantage of increased coverage area but it involves increased message latency and nodes synchronization.

2.4. Coexistence of IEEE 802.15.4 with Other Communication Protocols in Home Automation Networks. Several works in the literature analyze the coexistence of IEEE 802.15.4 with other networks protocols in home automation applications. In [31], a tunneling solution that allows running KNX/EIB over IEEE 802.15.4 links is presented. The authors analyze wireless sensor and actuator networks as an alternative to wired solutions in the home and building automation domain because several technologies that fulfill the specific requirements of this class of wireless networks have reached commercial status. The approach proposed by authors emulates the properties of the KNX/EIB wired medium via wireless communication, over an IEEE 802.15.4 network, allowing a seamless extension. Moreover, this novel architecture provides a basic level of communications security using a shared key through standard IEEE 802.15.4 security mechanism. As future works, the authors aim to a better evaluation of proposed approach performance, in terms of the effects of contention occurring on the tunneling medium. The use of 6LoWPAN and IEEE 802.15.4 protocols has been presented in [27], while 6LoWPAN, IPv6, and IEEE 802.15.4 protocols are also used in [32]. The authors propose a prototypical implementation of a home automation network that uses IPv6 over 6LoWPAN to control home applications. The proposed implementation is based on an embedded web server which, connected over a low-power IEEE 802.15.4 network, provides the ability to remotely open and close an electric door lock. Through this architecture, it is also possible to control other electronic consumer devices such as heating, air conditioning, lighting systems, and many others. The use of the proposed approach can offer many benefits for energy conservation, and, at the same time, it can involve new usage patterns in home automation applications, such as assisted living or smart grids. In [33] the development process of a smart home network is presented based on IEEE 802.15.4/ZigBee technology with the combination of SAANet, a smart home appliance communication protocol. The SAANet protocol aims at solving the data recognition between different types of devices because most of ZigBee devices profiles were not built completely. Therefore, the combination of ZigBee and SAANet protocols can be a solution to solve several problems. The integration between the two protocols has been successfully applied in order to achieve a supervisory home control system. The approach proposed by authors implements the functions of entrance control, temperature and humid sensing, and appliance control. A methodology to measure and avoid WiFi interference while deploying and installing ZigBee-based products in a home automation architecture is introduced in [34]. A detailed analysis shows that ZigBee products can successfully withstand interference from microwave ovens and Bluetooth devices but they are still vulnerable to high load WiFi traffic. Anyhow, the authors come to the conclusion that ZigBee can coexist with WiFi in a typical home environment if several preventative measures are taken into account. The recommendations to avoid WiFi interference, that authors derived experimentally, are to place WiFi router no closer than 5 meters of window shutters, and, moreover, it would be appropriate to use a frequency offset of at least 20 MHz between ZigBee and WiFi. However, other factors, such as traffic type, might also affect the performance of a system under WiFi interference. In future works, the authors focus on a more thorough study, taking into account these factors and using real user traffic instead of synthetically generated traffic.

3. The Proposed Approach

In this work, a two-tiered architecture in home automation environment (Figure 2) is shown. The first tier is characterized by a WSN in which devices are organized in home cells (HCs). Each HC is managed by a PAN coordinator that provides several modules.

(i) Ethernet module: it is the interface through which it is possible to establish a wired connection between each home cell and the real-time Ethernet backbone.

(ii) The IEEE 802.15.4 module through which the PAN coordinator receives and processes data detected by its home devices (HDs).

(iii) Scheduling module: this module is a quality of service (QoS) manager for real-time (RT) communications and dynamically decides transmission priorities of HDs using an approach based on rate monotonic (RM) and priority-based CSMA/CA (PB).

As already said, main system devices are home devices (HDs) and PAN coordinators. Each HD sends data acquired to its PAN coordinator and can be either an IEEE 802.15.4 reduced function device (RFD) or a full function device (FFD) in a clustered network. This paper addresses several advantages in the use of a novel intracell scheduling approach combined with the use of CSMA/CA-PB. The PAN coordinators are
responsible for data transmission of their associated nodes and for scheduling traffic decisions within their respective home cells.

The intracell scheduling in this architecture is realized through the preallocation of guaranteed time slots to devices involved in transmissions of periodic messages through the RM scheduling algorithm [20]. The GTS list contains the addresses of all devices interested to transmit. Each device will wait its turn according to its address position in the GTS List and then it will transmit using its allocated GTS. In case of high workloads or high number of nodes, it is possible to use the CSMA/CA-PB. The use of GTSs, allocated with RM, guarantees a deterministic allocation of slots. Consider

(i) a set of messages $M_i$, each one with relative deadline ($d_i$) equal to the period ($T_i$);
(ii) online scheduling;
(iii) nonpreemption.

Rate monotonic and earliest deadline first (EDF) [20] produce the same schedule. Under these assumptions, we could also use the EDF algorithm. Figure 3 demonstrates how 7 messages, each with $d_i = T_i$ and a certain computational time ($C_i$), as described by Table 1, can indifferently be scheduled using RM or EDF.

It is important to remind that in case of RM algorithm, the schedulability is guaranteed if

\[
\left( \sum_{i=1}^{n} \frac{C_i}{T_i} \right) \leq 0.68. 
\]

Otherwise, in case of EDF algorithm, the schedulability is guaranteed if

\[
\left( \sum_{i=1}^{n} \frac{C_i}{T_i} \right) \leq 1. 
\]

It is also possible to have a guarantee about messages schedulability, in accordance with deadlines, through the known Jeffay’s theorem [20]. A set of periodic requests (messages) is scheduled using a nonpreemptive algorithm if two conditions are met. The first equation (1) relates to system utilization (in terms of bandwidth, as we are dealing with

\[
\begin{array}{c|c|c|c}
\text{Message} & d_i = T_i & C_i & U_i \\
\hline
M_1 & 5 & 1 & 0.2 \\
M_2 & 10 & 2 & 0.2 \\
M_3 & 15 & 1 & 0.06 \\
M_4 & 15 & 1 & 0.06 \\
M_5 & 30 & 1 & 0.03 \\
M_6 & 30 & 2 & 0.06 \\
M_7 & 30 & 1 & 0.03 \\
\end{array}
\]
the transmission of packets), whereas the second equation (2) refers to the system demand.

**Theorem 1.** A system can schedule a set of periodic requests using nonpreemptive EDF algorithm if Jeffay’s conditions ((2) and (3)) are met:

\[
U_{tot} = U_p + U_S = \left( \sum_{i=1}^{n} \frac{C_i}{T_i} + U_S \right) \leq 1, \tag{3}
\]

\[
1 < i \leq n; \quad \forall L, T_1 < L < T_n : L \geq C_i + \sum_{j=i}^{n-1} \left( \frac{L-1}{T_j} \right) C_j. \tag{4}
\]

The periodic traffic flows are represented by a set of periodic variables \( \tau_p = \{p_1, p_2, \ldots, p_n\} \), where \( p_i = (C_i, T_i) \), sorted in a nondecreasing order by period (i.e., for any pair of variables \( p_i \) and \( p_j \), if \( i < j \) then \( T_i \geq T_j \)), and \( C_i \) is the transmission time for a periodic traffic flow generated by \( i \)th wireless node.

Equation (3) relates to the system utilization (in terms of bandwidth, as we are dealing with the transmission of packets), whereas (4) refers to the system demand. Equation (3) defines that total bandwidth utilization must not exceed 1; \( U_p \) is the utilization factor for periodic traffic while \( U_S \) is the utilization factor for sporadic and aperiodic traffic flows (i.e., server utilization). The inequality in (3) refers to a least upper bound on bandwidth demand that can be achieved in an interval of length \( L \). This interval starts when the periodic variable is invoked and ends before the relative deadline. Then, a set of variables is schedulable if the demand in the interval \( L \) is less than or equal to the length of the interval. In this paper, we choose to work according to slotted CSMA/CA as provided by the standard. Scheduling management through preallocated GTS can be considered efficient. The \( \text{RM} + \text{CSMA/CA-PB} \) approach, proposed in this paper, guarantees the access to the medium for periodic transmissions providing a division into three priority classes for all transmission regulated by CSMA/CA in contention access period: high priority, medium priority, and low priority. The three priority classes have been created modifying two standard parameters.

(i) \( CW \) (contention window): it is the contention window length, in other words, the number of backoff periods during which it is necessary to listen to the channel before the transmission.

(ii) \( BE \) (backoff exponent): it is the variable that determines the number of backoff periods the device shall wait before channel access attempts.

The number of waiting periods (CW) is a random number inside the range \([0, 2^{BE} - 1]\) where \( \text{macMinBE} < BE < \text{macMaxBE} \).

In home automation environments, the coexistence of different traffic types must be taken into account. In order to define the priority class, BE and CW variables of the CSMA/CA have been used. BE has been considered as a variable in the range \( 1 \leq BE \leq 3 \). Considering that in each beacon interval, with \( n \) preallocated slots for GTS \((0 \leq n \leq 7)\), it is possible to use up to \( 15 - n \) slots for the CSMA/CA. As a consequence, it has been possible to define three priority classes as shown in Table 2.

These values must be set on each HC’s node in order to define the priority of each device. The choice of contention window and backoff exponential determines nodes transmission frequency. High-priority nodes will listen to the channel more frequently and with higher probability of transmission success. Clearly, this approach does not resolve the nondeterminism of the wireless channel but significantly reduces latencies of nodes involved in the contention access to the channel.

### 3.1 Probabilistic Analysis of IEEE 802.15.4 Transmissions through CSMA/CA-PB

Another aspect considered and proposed through this paper concerns the relationship between the probability that a station finds the channel free and the network throughput varying CW and BE parameters. As already proposed by several works in the literature [35–37], the CSMA/CA algorithm can be modeled through an M/G/1 queue. Consider

(i) \( n \): the number of nodes associated to a PAN coordinator;

(ii) \( N \): the total number of network nodes (associated and not);

(iii) \( \lambda \): packets generation rate (according to a poisson process);

(iv) \( T_{TX} \): the fixed packet transmission time;

(v) \( Wl \): network workload;

(vi) \( T_{\text{turn}} \): turnaround time;

(vii) \( T_{ACK} \): transmission time for ACK packet;

(viii) \( \sigma \): backoff slot duration.

The probability \( (\alpha) \) of channel busy during the contention window \( CW \), the packet loss probability \( P_{\text{loss}} \), and the average delay \( E[D_{\text{HOL}}] \) are given by the nonlinear equations system:

\[
\alpha = \frac{(n - 1)(1 - P_{\text{loss}}) Wl \cdot (CW + T_{TX} + 2T_{\text{turn}} + T_{ACK})}{(1/\lambda) + Wl + E[D_{\text{HOL}}]},
\]

\[
P_{\text{loss}} = \alpha^{N + 1},
\]

| Priority   | CW     | macMinBE–macMaxBE |
|------------|--------|-------------------|
| High priority | 1     | 0-1               |
| Medium priority | 1-2  | 1-2               |
| Low priority   | 2     | 2-3               |
| Standard       | 2     | 3-5               |
\[ E[D_{\text{HoL}}] = \sum_{v=0}^{N} \alpha^v (1 - \alpha) \left\{ \sum_{i=0}^{v} \frac{W_i - 1}{2} \sigma + (v + 1) \text{CW} \right\} \]
\[ + \alpha^{N+1} \left\{ \sum_{i=0}^{N} \frac{W_i - 1}{2} \sigma + (N + 1) \text{CW} \right\}. \] (5)

The equations previously expressed in the variables \( \alpha \), \( P_{\text{loss}} \), and \( E[D_{\text{HoL}}] \) can be numerically solved in order to obtain the value \( \alpha \) of busy channel probability, from which afterwards it is possible to obtain the throughput value according to

\[ \text{TH} = \frac{n (1 - P_{\text{loss}}) W_l \cdot T_{\text{TX}}}{(1/\lambda) + W_l \cdot (E[D_{\text{HoL}}] + T_{\text{TX}} + 2T_{\text{turn}} + T_{\text{ACK}})}. \] (6)

The term \( (E[D_{\text{HoL}}] + T_{\text{TX}} + 2T_{\text{turn}} + T_{\text{ACK}}) \) represents the waiting period in an \( M/G/1 \) queuing system. Figure 4 analyzes system’s performance in terms of transmission probability behavior varying the number of nodes in the network.

It is easily observable that the transmission probability of low priority nodes is slightly better than the standard, while medium and high priority nodes have a higher transmission probability.

### 4. Performance Evaluation

Performance of our approach has been tested through a real experimental scenario implemented using IRIS MTS300 [38] and MTS300 boards from Crossbow/Memsic and taking into account requirements of an IEEE 802.15.4 network described in [39]. Tests have been conducted on a star topology network with 9 RFID devices (HD) and a gateway (PAN coordinator). In particular, 3 “high priority” nodes, 2 “medium priority” nodes, and 4 “low priority” nodes have been considered as shown in Figure 5.

Varying CW and BE parameters, 4 case analyses have been identified, as better explained through Table 3.

#### Case 1.

Consider the following:

(i) high priority nodes → CW = 1, BE = 1;

(ii) medium priority nodes → CW = 1, BE = 2;

(iii) low priority nodes → CW = 2, BE = 3.

Figures 6 and 7 show performance obtained in Case 1. Figure 6 shows how higher priority nodes are characterized by throughput/workload (Th/Wl) values higher than nodes with lower priority. On average, high priority nodes obtain better performance with the use of CSMA/CA-PB than the standard. This is due to the fact that they have higher probability to transmit. In other words, they have a high reduction of waiting times during radio channel accesses attempts. On the contrary, lower and medium priority nodes measure values lower than the standard because for them CW = 2 and BE = 3. Figure 7 shows improvements in terms of Th/Wl obtained by each priority class. In general, total network Th/Wl is better than the standard but Th/Wl measured by all low priority nodes is lower.

#### Case 2.

Consider the following:

(i) high priority nodes → CW = 1, BE = 2;

(ii) medium priority nodes → CW = 1, BE = 2;

(iii) low priority nodes → CW = 2, BE = 3.

Figures 8 and 9 show performance obtained in Case 2. Figure 8 shows Th/Wl values measured on each node. Even in this case, higher priority nodes reach throughput/workload (Th/Wl) values higher than nodes with lower priority. But, it is possible also to see that even medium priority nodes obtain better performance through our approach. At the same time, differences in results, between CSMA/CA-PB and the standard, decrease also for low priority nodes. Figure 9 shows improvements in terms of Th/Wl classified for priority classes. Using a priority classification of traffic flows, the obtained Th/Wl of the whole network is higher than the standard and, in this case, even the Th/Wl measured by all low priority nodes is better than the standard.
Figure 5: Test-bed scenario.

Case 3. Consider the following:

(i) high priority nodes \(\rightarrow CW = 1, BE = 1\);
(ii) medium priority nodes \(\rightarrow CW = 2, BE = 2\);
(iii) low priority nodes \(\rightarrow CW = 2, BE = 3\).

Figures 10 and 11 show performance obtained in Case 3. Figure 10 shows Th/Wl values measured on each node. Even in this case, higher priority nodes reach throughput/workload (Th/Wl) values higher than nodes with lower priority. Just nodes 1 and 3 measure the worst performance than the standard. This is due to the fact that the traffic flows classification, based on priorities, supports a more frequent transmission of messages with higher priority, resulting in a slight increase of waiting times for some nodes having medium or low priority. Figure 11 shows improvements in terms of Th/Wl classified for priority classes. Results clearly
show how, using the proposed algorithm, the Th/Wl ratio of the whole network is higher than Th/Wl obtained using the standard algorithm. As already explained in Figure 10, the Th/Wl obtained by all low priority nodes is lower than the standard because they can transmit with lower frequency.

**Case 4.** Consider the following:

(i) high priority nodes → CW = 1, BE = 2;
(ii) medium priority nodes → CW = 2, BE = 2;
(iii) low priority nodes → CW = 2, BE = 3.

Finally, Figures 12 and 13 show performance obtained in Case 4. In particular, Figure 12 shows Th/Wl values measured on each node. Even in this case, higher priority nodes reach throughput/workload (Th/Wl) values higher than nodes with lower priority. This case study produced best performance results. In fact, just node 3 obtained the worst performance, and generally, even low priority nodes obtained better performance than the standard algorithm, as it is possible to see through Figure 13.

**5. Conclusions**

In this paper, a novel scheduling mechanism for periodic traffic flows management has been proposed in order to support the development of home-automated networks. The main aim is to reduce latencies of channel access attempts of network embedded devices in home automation applications. This new approach, called rate monotonic + CSMA/CA-PB,
provides the preallocation of guaranteed time slots (GTSs) through the rate monotonic algorithm for those devices which want to transmit periodic messages. As known, the standard algorithm provides a FIFO allocation of GTSs. Moreover, this approach reduces waiting times of nodes competing for the medium access using the CSMA/CA in contention access period through a priority classification of network traffic flows. An experimental real scenario, based on the IEEE 802.15.4 standard protocol, has been deployed in order to demonstrate benefits introduced by this approach. Varying the contention window (CW) and the backoff Exponential (BE) parameters, it has been possible to produce a traffic flows classification based on priorities. Obtained results show how high priority nodes will reach better performance than those with lower priority. Measured performances are generally better than the IEEE 802.15.4 standard that does not differentiate network traffic flows.

**References**

[1] Z. Ruyan, L. Huifang, H. Shijun, and W. Dongyun, “Data processing and node management in wireless sensor network,” in *Proceedings of the 1st International Symposium on Computer Network and Multimedia Technology* (CNMT ’09), pp. 1–4, December 2009.

[2] M. Colotta, G. Pau, V. M. Salerno, and G. Scatà, “A fuzzy based algorithm to manage power consumption in industrial wireless sensor networks,” in *Proceedings of the 9th IEEE International Conference on Industrial Informatics* (INDIN ’11), pp. 151–156, 2011.

[3] M. Colotta, L. Gentile, G. Pau, and G. Scatà, “A dynamic algorithm to improve industrial wireless sensor networks management,” in *Proceedings of the 38th Annual Conference of IEEE Industrial Electronics* (IECON ’12), pp. 2802–2807, 2012.

[4] V. C. Gungor and G. P. Hancke, “Industrial wireless sensor networks: challenges, design principles, and technical approaches,” *IEEE Transactions on Industrial Electronics*, vol. 56, no. 10, pp. 4258–4265, 2009.

[5] M. Colotta, L. Lo Bello, and O. Mirabella, “An innovative frequency hopping management mechanism for Bluetooth-based industrial networks,” in *Proceedings of the 5th International Symposium on Industrial Embedded Systems* (SIES ’10), pp. 45–50, July 2010.

[6] M. Colotta, V. Conti, G. Pau, G. Scatà, and S. Vitabile, “Fuzzy techniques for access and data management in home automation environments,” *Journal of Mobile Multimedia*, vol. 8, no. 3, pp. 181–203, 2012.

[7] Y. Li, J. Maorong, G. Zhenru, Z. Weiping, and G. Tao, “Design of home automation system based on ZigBee wireless sensor network,” in *Proceedings of the 1st International Conference on Information Science and Engineering* (ICISE ’09), pp. 2610–2613, December 2009.
[8] M. Collotta, G. Nicolosi, E. Toscano, and O. Mirabella, “A ZigBee-based network for home heating control,” in *Proceedings of the 34th Annual Conference of IEEE Industrial Electronics (IECON ’08)*, pp. 2724–2729, November 2008.

[9] A. Pascale, M. Nicoli, F. Deflorio, B. Dalla Chiara, and U. Spagnolini, “Wireless sensor networks for traffic management and road safety,” *IET Intelligent Transport Systems*, vol. 6, no. 1, pp. 67–77, 2012.

[10] M. Collotta, G. Pau, V. M. Salerno, and G. Scatà, “A novel road monitoring approach using wireless sensor networks,” in *Proceedings of the 6th International Conference on Complex, Intelligent and Software Intensive Systems (CISIS ’12)*, pp. 376–381, 2012.

[11] L. Yong-Min, W. Shu-Ci, and N. Xiao-Hong, “The architecture and characteristics of wireless sensor network,” in *Proceedings of the International Conference on Computer Technology and Development (ICCTD ’09)*, vol. 1, pp. 561–565, 2009.

[12] S. Vitabile, V. Conti, M. Collotta et al., “A real-time network architecture for biometric data delivery in Ambient Intelligence,” *Journal of Ambient Intelligence and Humanized Computing*, 2012.

[13] IEEE Standard for Information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications.

[14] J. She Jin, J. Jin, Y. Hui Wang, K. Zhao, and J. Jun Hu, “Development of remote-controlled home automation system with wireless sensor network,” in *Proceedings of the 5th IEEE International Symposium on Embedded Computing (SEC ’08)*, pp. 169–173, Beijing, China, October 2008.

[15] L. Yanfei, W. Cheng, Y. Chengbo, and Q. Xiaojun, “Research on ZigBee wireless sensors network based on ModBus protocol,” in *Proceedings of the International Forum on Information Technology and Applications (IFITA ’09)*, vol. 1, pp. 487–490, May 2009.

[16] C. Jin and T. Kuntz, “Smart home networking: combining wireless and powerline networking,” in *Proceedings of the 7th International Conference on Wireless Communications and Mobile Computing (IWCMC ’11)*, pp. 1276–1281, 2011.

[17] “802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)—June 2006 IEEE standard for information technology. Part 15.4.

[18] M. Collotta, G. Pau, V. M. Salerno, and G. Scatà, “A distributed load balancing approach for industrial IEEE 802.11 wireless networks,” in *Proceedings of IEEE Conference on Emerging Technologies & Factory Automation (ETFA ’12)*, pp. 1–4, 2012.

[19] M. Collotta, L. Lo Bello, E. Toscano, and O. Mirabella, “Dynamic load balancing techniques for flexible wireless industrial networks,” in *Proceedings of the 36th Annual Conference on IEEE Industrial Electronics Society (IECON ’10)*, pp. 1329–1334, 2010.

[20] G. C. Buttazzo, *Hard Real-Time Computing Systems—Predictable Scheduling Algorithms and Applications*, Springer, 3rd edition, 2011.

[21] J. A. Nazabal, P. L. Iturri, L. Azpilicueta, F. Falcone, and C. F. Valdivielso, “Performance analysis of IEEE 802.15.4 compliant wireless devices for heterogeneous indoor home automation environments,” *International Journal of Antennas and Propagation*, vol. 2012, Article ID 176383, 14 pages, 2012.

[22] C. A. M. Bolzani, C. Montagnoli, and M. L. Netto, “Domotics over IEEE 802.15.4—a spread spectrum home automation application,” in *Proceedings of the 9th IEEE International Symposium on Spread Spectrum Techniques and Applications (ISSSTA ’06)*, pp. 396–400, August 2006.

[23] M. A. B. Sarjari, R. A. Rashid, M. R. A. Rahim, and N. H. Mahalin, “Wireless home security and automation system utilizing ZigBee based multi-hop communication,” in *Proceedings of the 6th IEEE National Conference on Telecommunication Technologies and 2nd IEEE Malaysia Conference on Photonics (NCTT-MCP ’08)*, pp. 242–245, August 2008.

[24] A. Kailas, V. Cecchi, and A. Mukherjee, “A survey of communications and networking technologies for energy management in buildings and home Automation,” *Journal of Computer Networks and Communications*, vol. 2012, Article ID 932181, 12 pages, 2012.

[25] D. M. Han and J. H. Lim, “Smart home energy management system using IEEE 802.15.4 and ZigBee,” *IEEE Transactions on Consumer Electronics*, vol. 56, no. 3, pp. 1403–1410, 2010.

[26] F. Xia, R. Hao, Y. Cao, and L. Xue, “A survey of adaptive and real-time protocols based on IEEE 802.15.4,” *International Journal of Distributed Sensor Networks*, vol. 2011, Article ID 212737, 11 pages, 2011.

[27] P. Yi, A. Iwayemi, and C. Zhou, “Building automation networks for smart grids,” *International Journal of Digital Multimedia Broadcasting*, vol. 2011, Article ID 926363, 12 pages, 2011.

[28] H. Seok Kim, J. H. Song, and S. Lee, “Energy-efficient traffic scheduling in IEEE 802.15.4 for home automation networks,” *IEEE Transactions on Consumer Electronics*, vol. 53, no. 2, pp. 369–374, 2007.

[29] W. Choi and S. Lee, “A novel GTS mechanism for reliable multihop transmission in the IEEE 802.15.4 Network,” *International Journal of Distributed Sensor Networks*, vol. 2012, Article ID 796426, 10 pages, 2012.

[30] N. Ferreira and J. A. Fonseca, “Using time-triggered communications over IEEE 802.15.4,” in *Proceedings of the 12th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA ’07)*, pp. 1384–1387, September 2007.

[31] C. Reinisch, W. Kastner, G. Neugschwandtner, and W. Granzer, “Wireless technologies in home and building automation,” in *Proceedings of the 5th IEEE International Conference on Industrial Informatics (INDIN ’07)*, vol. 1, pp. 93–98, June 2007.

[32] B. M. Dorge and T. Scheffler, “Using IPv6 and 6LoWPAN for home automation networks,” in *Proceedings of IEEE International Conference on Consumer Electronics—Berlin (ICCE ’11)*, pp. 44–47, September 2011.

[33] Y.-P. Tsou, J.-W. Hsieh, C.-T. Lin, and C.-Y. Chen, “Building a remote supervisory control network system for smart home applications,” in *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics ((SMC ’06)*, vol. 3, pp. 1826–1830, October 2006.

[34] F. Dominguez, A. Touhafi, J. Tiete, and K. Steenhaut, “Coexistence with WiFi for a home automation ZigBee product,” in *Proceedings of the 19th IEEE Symposium on Communications and Vehicular Technology in the Benelux (SCVT ’12)*, pp. 1–6, 2012.

[35] T. Ok Kim, J. Soo Park, H. Jin Chong, K. Jae Kim, and B. Dae Choi, “Performance analysis of IEEE 802.15.4 non-beacon mode with the unslotted CSMA/CA,” *IEEE Communications Letters*, vol. 12, no. 4, pp. 238–240, 2008.

[36] Z. Chen, C. Lin, H. Wen, and H. Yin, “An analytical model for evaluating IEEE 802.15.4 CSMA/CA protocol in low-rate
wireless application," in Proceedings of the 21st International Conference on Advanced Information Networking and Applications Workshops (AINAW ’07), vol. 2, pp. 899–904, May 2007.

[37] J. He, Z. Tang, H.-H. Chen, and Q. Zhang, "An accurate and scalable analytical model for IEEE 802.15.4 slotted CSMA/CA networks," IEEE Transactions on Wireless Communications, vol. 8, no. 1, pp. 440–448, 2009.

[38] http://www.memsic.com/support/documentation/wireless-sensor-networks/category/7-datasheets.html?download=135%-3Airis.

[39] M. Collotta, L. Lo Bello, and E. Toscano, "A proposal towards flexible wireless communication in factory automation based on the IEEE 802.15.4 protocol," in Proceedings of IEEE Conference on Emerging Technologies & Factory Automation (ETFA ’09), pp. 1–4, September 2009.