Computer Networks 134 (2018) 127–139

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

A fuzzy-based approach for energy-efficient Wi-Fi communications in dense wireless multimedia sensor networks

Mario Collotta[a,*], Giovanni Pau[a], Daniel G. Costa[b]

[a] Computer Enginering and Networks Laboratory, Kore University of Enna, Italy
[b] State University of Feira de Santana, Feira de Santana, Brazil

ARTICLE INFO

Article history:
Received 2 December 2016
Accepted 17 January 2018
Available online 31 January 2018

Keywords:
Wireless Multimedia Sensor Networks (WMSN)
Fuzzy Logic Controller (FLC)
Energy efficiency
Multimedia streaming

ABSTRACT

Wireless multimedia sensor networks can provide valuable information for many monitoring and control applications, which can process scalar data, still images, audio and video streams. However, multimedia streaming is still very challenging for those networks, since energy constraints limit the attainable bandwidth for data packet transmissions. In some cases, dense sensor networks may have many source nodes streaming at the same time and such transmission demand may not be supported by the network protocols and defined links. Actually, for networks based on IEEE 802.15.4 protocol, multimedia streaming may be unfeasible for many scenarios, even with small numbers of sensors, severely restricting the deployment of multimedia sensor nodes. However, other standards as IEEE 802.11 could provide acceptable bandwidth for multimedia streaming, although energy efficiency is not a major concern for it. In this context, this paper proposes an energy-efficient approach that provides high bandwidth with optimized energy consumption, directly benefiting wireless multimedia sensor networks. A fuzzy-based solution is defined to determine whether Wi-Fi access points should be switched off when they are underutilized, reducing energy consumption while keeping network performance at acceptable levels.

1. Introduction

In recent years, Wireless Multimedia Sensor Networks (WMSN) have been considered for a large set of monitoring and control applications in a varying number of scenarios, as in industrial automation, public security, traffic control, health assistance, visual surveillance, among many others [1–3]. Due to the decrease in the price of wireless and sensing technologies, WMSN can be designed to operate in different network backbones, integrating Internet services with application-specific networks [4–6]. The Internet of Things (IoT) concept has arise in this context of convergent communications, where traditional Internet standards may be merged into the wireless sensor networks world [7–9].

Wireless multimedia sensor networks may be composed of many source nodes that will stream continuously or for defined periods of time. In such cases, there may be a lot of information that will flow through the network toward sink nodes. For ad hoc networks composed of low-rate wireless personal area networks technologies, such as IEEE 802.15.4 MAC protocol [10], such large amount of packets may not be delivered due to the provided low bandwidth. Moreover, too many packets may be relayed through ad hoc paths, rapidly consuming energy in sensor nodes. For dense WMSN with many active multimedia source nodes, MAC protocols for high bandwidth should be considered, where IEEE 802.11 [11] networks come as a cheap and reasonable solution for this scenario. If we define that IEEE 802.11 (Wi-Fi) Access Points (APs) will play the role of sinks, high bandwidth can be provided for WMSN.

It is necessary to highlight that wireless communications raise several concerns, including that of power consumption, which are relevant for Wi-Fi and WMSN contexts alike. In recent years, there have been some efforts in order to try to solve this problem by introducing wireless communication systems with low energy consumption [12–16]. Moreover, the average power consumption of network equipments has been estimated to be 25 GW during daily operation worldwide (yearly average in 2008) [17] and a single corporate WLAN may feature more than 5000 Wi-Fi APs [18]. But, as shown in [19], these values have risen over the past few years. On the contrary, considering the existing network design approaches, it is useful to note that they lack several key elements. First of all, traffic demand and user density are not considered. In fact, the coverage-based optimization approaches may appear insufficient for networks where user density and traffic load is high. In the near future, WLAN and WMSN environments will have higher user

* Corresponding author.
E-mail addresses: mario.collotta@unikore.it (M. Collotta), giovanni.pau@unikore.it (G. Pau), danielgcosta@uefs.br (D.G. Costa).

https://doi.org/10.1016/j.comnet.2018.01.041
1389-1286/

concentration, with applications demanding increased data rates, but energy efficiency will be still a major design concern.

Wireless LAN may be designed beyond just a basic complete coverage strategy, since WLANs with redundant layers of access points may also be defined [20]. The main aim of these redundant layers is to provide a very high bandwidth in situations where hundreds of clients simultaneously run bandwidth-intensive and delay-sensitive applications. However, as shown in [21], the peak demand on the network rarely occurs as the APs are utilized mostly during the day, and even fewer during nights and weekends. For this reason the majority of the APs frequently remain idle, which means they serve no users in the network. If the WMSN context is also considered, multimedia streaming may also significantly variate along the time.

Actually, multimedia sensors may have different transmission patterns that may change along the time. Camera-enabled sensors may transmit images or video streams, with different bandwidth demands. Scalar sensors may also be deployed to retrieve small amounts of information. Moreover, source nodes may transmit data packets in real-time, requiring low latency and jitter [1,2]. In order to provide an energy-efficient solution for this scenario, with many source nodes connected to 1-hop Wi-Fi access points, this paper proposes a novel power management approach based on a fuzzy solution. This approach defines a dynamic network topology because the number of active APs is reduced when they are not used or underutilized, potentially saving energy while not considerable degrading the network performance.

Some recent research works have focused on soft computing techniques since they fit themselves well in wireless networks applications. They have been proposed for the construction of new generation artificial intelligence and for solving non-linear and mathematically un-modeled systems. The main aim of soft computing techniques is to evaluate, to decide, to monitor and to measure in several application fields, emulating and using human ability to perform the above activities on the basis of experiences. For this reason, soft computing techniques are applied in several research fields and they have found also applications in energy consumption and power management [22–24]. Since the inputs and the outputs of Fuzzy Logic Controllers (FLCs) are real variables mapped with a non-linear function, they are appropriate for various engineering problems, especially for complex problems where classical control methods do not achieve comparatively favorable results.

In fact, the turning on/off of devices is considered as the output of a FLC and it is dynamically calculated considering the distance from sensor nodes with respect to the AP, the number of connected sensors and the average throughput of access points. The distance value is calculated by using the Receiving Signal Strength Indicator (RSSI). In this way, the wireless communication coverage is still maintained and only redundant coverage is reduced. Furthermore, it is useful to note that when transmission demands increase, e.g. due to scheduled monitoring or in response to critical events in triggered-based WMSN [25], wireless resources are powered on in order to scale resource and coverage redundancy proportionately. The main contribution of this paper is that the proposed fuzzy-based solution reduces the energy wastage without adversely impacting coverage and monitoring performance in high-density WMSN.

The considered communication scenario is very broad and can benefit a lot of WMSN, specially in dense deployment. We then expect the following contributions. First, as wireless multimedia sensor networks may be used for extensive monitoring applications, where some or all source nodes may be streaming high quality video, typical MAC protocols as IEEE 802.15.4 cannot support such bandwidth demand. We then consider IEEE 802.11 Wi-Fi networks as the basis for dense WMSN. Second, as packet relaying may be too degrading in terms of energy consumption, multiple sinks can be used for 1-hop communications. We then consider Wi-Fi access points as sinks. Finally, the network activity may significantly change along the time, with periods of very high and very low transmission flows. In such way, the number of active access points may be dynamically managed, according to parameters of the network. Doing so, energy consumption may be optimized in the network as a whole. To the best of our knowledge, this approach has not been proposed before.

This paper is organized as follows. Section 2 introduces existing approaches in the literature. Section 3 introduces the network architecture and describes the FLC. Section 4 addresses the performance obtained in test campaigns and compares the results of comparative assessments with other approaches, presenting also an implementation of the proposed solution on Commercial Off-The-Shelf (COTS) hardware, and, finally, Section 5 concludes the paper and gives hints for future work.

2. Related works

Several research works in last years have addressed many relevant issues that directly or indirectly influence our investigation. Among them, some of the most relevant works are highlighted in this section, covering subjects related to power management in WLAN and WMSN, as well as fuzzy-based optimization of multimedia networks.

2.1. Wireless multimedia

Multimedia packets can be transmitted in different wireless technologies, but QoS (Quality of Service) parameters as latency, jitter and throughput should always be considered when required by applications. In general, many works have proposed optimizations to such communications, aiming at higher performance.

In wireless sensor networks, multimedia streaming imposes many challenges that have been addressed in different works [1,26]. The work in [27] proposed the Reliable Synchronous Transport Protocol (RSTP) for synchronization of image transmission from multiple source sensors. As progressive coding is used for image processing [28], received images may be displayed entirely, but with low quality, when transmitted over low-bandwidth links and error-prone environments. In [29], authors proposed a computational solution to mitigate congestion by reduction on the data transmission rate. Exploiting the Discrete Wavelet Transform (DWT) coding technique, the quality of received images are not significantly reduced. In a different way, the work in [30] defined a cross-layer optimization for video transmissions in wireless multimedia sensor networks. Authors exploited multipath routing, where paths with lower latency should be used more often to transmit packets containing encoded video, saving energy and potentially prolonging the capability of the network to deliver real-time multimedia traffic. In [31], a cross-layer approach for video streaming in WMSN was proposed, exploiting the concept of Compressive Sensing, aiming at the adjustment of transmission rates. For all these works, the transmission rate is adjusted for increased efficiency, mainly because the network cannot provide the required bandwidth. Actually, when there are many source nodes streaming high-quality video, the bandwidth demand may be dramatic for sensor networks.

In order to better support multimedia streaming in wireless sensor networks, IEEE 802.11 MAC protocol may be employed. And some research works have addressed challenges of Wi-Fi-based WMSN. In [32], authors proposed differentiated treating of multimedia packets in MAC layer according to the relevance of the encoded data for MPEG-4 video streams. That work exploits

IEEE 802.11s extension [33], which provides QoS-based transmission classes. Differently, in [34], the IEEE 802.11e extension is considered for wireless multimedia sensor networks and authors investigated some MAC access control mechanisms of this protocol. Actually, multimedia streaming has also been investigated in IP-based networks, exploiting some of IEEE 802.11 extensions [35]. Nonetheless, in most cases, energy consumption was not a concern. For dense wireless multimedia sensor networks, however, energy conservation should be carefully addressed, fostering innovative research in this area.

2.2. Power consumption reduction of WLANs

In the literature, several works in the field of WLANs that aim to reduce the power consumption efficiently have been proposed. In fact, the reduction of energy consumption can be achieved by introducing intelligence into the network infrastructure by employing, for example, different kinds of algorithms [36] or MAC access protocols [37].

Considering the internal architecture of the APs normally deployed in WLANs, in [38] it is observed that the largest amount of power consumption is due to base components, rather than transmission circuits, so that an AP consumes approximately the same amount of power, independently from the traffic that is flowing through it. For this reason the shut-down of unused APs can be a viable solution in order to save energy.

The design and the performance evaluation of a new mechanism that, by controlling the accesses to the shared transmission channel of a WLAN, leads each station to an optimal power consumption level is introduced in [39]. Considering the IEEE 802.11 protocol, the authors initially derived the optimal average power consumption levels required for a frame transmission analytically and subsequently define a novel mechanism that can be adopted to enhance the performance of the IEEE 802.11 protocol in terms of power saving. Simulation results show that the enhanced protocol closely approximates the optimal power consumption level, and provides a channel utilization close to the theoretical upper bound for the IEEE 802.11 protocol capacity. However, the results are only obtained by simulations and therefore it is not clear how the approach proposed by the authors could be applied on real devices.

The authors of [40] present a deep study focused on the power consumption of WLANs and propose a new technique in order to reduce the power consumption of APs. In fact, a centralized network in which a controller node is capable of taking appropriate power saving decisions in presented. Thanks to this controller, the approach proposed by the authors has a significant impact in term of power saving and cost of communication network. However, the complexity of implementation is not analyzed in detail by the authors.

On the contrary, the authors of [41] note that several solutions have been presented in order to reduce the power consumption in WLANs. However, most of them are expensive to install and to manage especially for large legacy deployments. For this reason, in order to overcome this limitation they propose a virtual power consumption monitoring solution capable of estimating in real-time the actual power consumption of Wi-Fi APs. The result of a real experimental scenario show that the proposed approach can provide a precise estimation of the power consumed by a typical IEEE 802.11 AP. However, only one AP and one client are used in the experimental scenario and for this reason it is not easy to deduce the behavior of the solution proposed by the authors in contexts with several APs and connected clients.

In [42] the authors focus on the energy-conservation problem in IEEE 802.11 WLANs in the presence of transmission-strategy diversity. An energy-efficient scheme that allocates airtime shares to contending stations so as to achieve combined airtime and energy-conservation fairness is introduced. Simulation results show that, when the energy-conservation fairness is considered, both aggregate system throughput and overall system energy-efficiency can be improved significantly with all contending stations consuming a similar amount of energy. However, even in this case, the results are obtained through simulations and not on a real scenario.

In [43] the authors introduce a simple approximate queuing models in order to assess the effectiveness of other approaches, proposed to save energy in dense WLANs, based on the activation of APs according to the user demand. The authors consider a portion of a dense WLAN, where several APs are deployed in order to provide sufficient capacity to serve a large number of active users during peak traffic hours. Due to daily variations of the number of active users accessing the WLAN, some APs can be switched off to save energy when not all the capacity is needed. The results of a a real experimental scenario show that the energy saving achievable with the proposed model is quite substantial, from 40% to almost 60% if all APs are switched off at night. However, these results are not obtainable in the daytime because the APs are turned on. In fact, the authors, in their proposed solution, do not consider the switch off of the APs in daytime hours because they focus at night-time.

In conclusion, it is clear that several approaches in the literature can provide valuable support in order to improve the management of power consumption in WLAN and WMSN. However many of these approaches have not been evaluated through a real implementation, and therefore their validity can be questioned. Furthermore, even the approaches based on a fuzzy controller can be used to achieve the management of power consumption. For this reason, before the introduction of the approach proposed in this paper, it is useful to examine briefly literature works based on fuzzy approaches that aim to reduce the energy consumption in order to show that even soft computing techniques can be successfully applied in this research field.

2.3. Fuzzy approaches for the reduction of power consumption

Fuzzy logic controllers are suitable for managing Wireless LAN characterized by strongly varying conditions, that call for the adoption of “approximate” solutions, based on human reasoning. However, in the design of fuzzy logic controllers for this application, several factors must be considered, such as the computational complexity of the algorithm, the feasible implementation on COTS devices and the system scalability.

An energy-efficient self-organizing technique based on fuzzy logic systems both for enhancing the coverage of a wireless network to optimize the overall energy consumption is proposed in [44]. The energy is the main operating constraint in a self-deployment process. So, the energy used by each device is an important parameter. Simulation results show that the proposed approach achieves a stable deployment that maximizes coverage but also optimizes the overall energy consumption. However, two criticisms can be raised about the approach proposed by the authors. In fact, the results have been obtained with simulations and not in a real scenario and, mainly, it is obvious that the overall energy consumption optimization is not optimal since the authors also aim to maximize the coverage.

In this [45] a context-aware power management system, based on a fuzzy inference system, implemented as a widely-applicable middle-ware application is proposed. The authors test the proposed approach using streaming applications on a mobile phone and obtained results show energy reduction from 13% up to 50%. The approach proposed by the authors is promising and it would be interesting to evaluate its applicability in the APs. However, the fuzzy-based approach focuses on mobile devices.

The authors of [46] present a real time fuzzy logic controller approach used to design a power management strategy for a hybrid electric vehicle and to protect the battery from overcharging during the repetitive braking energy accumulation. The paper analyses and evaluates the performance considering several configurations during real time driving conditions and unknown driving cycle. Obtained results are promising and show how a fuzzy approach may be valid for the power management in contexts outside the WLANs.

In [47] a fuzzy energy-aware unequal clustering algorithm is introduced. The approach proposed by the authors aims to decrease the intra-cluster work of the cluster-heads that are either close to the base station or have low remaining battery power. For this reason, a fuzzy logic approach is adopted in order to handle uncertainties in cluster-head radius estimation. The proposed algorithm is compared with other approaches in the literature and results and the results show that it is much more efficient mainly from the energy point of view. These results show that a fuzzy-based approach can be valuable in terms of energy savings also in clustering algorithms. In fact, the authors of [48] introduce an approach that integrate a FLC and a fuzzy c-mean algorithm in order to improve the energy efficiency of a wireless network. In fact, the main aim of the authors is to obtain both a high energy efficiency and a longer lifetime in a wireless network cluster. Several simulations are carried out and the result demonstrate that using the approach proposed by the authors the lifetime of cluster is increased by more than 55%.

This Section has shown that in the literature there are several fuzzy-based approaches that aim to enhance the energy efficiency in several application fields. It is clear that a fuzzy mechanism can be introduced in order to improve the power consumption even in WLANs. However, most of the approaches in the literature did not focus on access networks, considering that access devices are the main energy consumers, mainly in IEEE 802.11 WLANs. For this reason, the fuzzy-based approach proposed in this paper, for the energy-aware management of access networks reducing the number of active access devices when they are underutilized, may be a viable solution in order to solve the energy efficiency problem.

The proposed system is lightweight, as the data sent through the wireless network are small (small integer numbers) and thus there is a little cost from both the communication and the processing point of view. The solution proposed in this work can be therefore implemented in COTS devices. In order to highlight this feature, the paper also shows the experimental results obtained through an implementation of the proposed controller on a real prototyping board (Section 4.2). The proposed approach is scalable, as it is able to manage also large WLAN. Another notable property of the proposed approach is its flexibility, as it is possible to increase/decrease the inference rules, thus increasing the accuracy without affecting the performance of both the wireless network and the controller.

3. The proposed approach

First of all, it is necessary to present the proposed network architecture. A densely deployed wireless multimedia sensor network, where the coverage areas of neighboring cells overlap each other, is considered in this paper. Several wireless cells that have the same coverage radius and several traffic loads with specific pattern compose the network. Specifically, in Fig. 1 the architecture of the wireless access network, on which the proposed approach is developed, is depicted. In the proposed solution, sensors are in the range of coverage of at least two APs, which is a typical scenario in WLANs implemented in businesses, enterprises and universities, and that may also be assumed for many WMSN scenarios. As depicted in Fig. 1, the Fuzzy Network Controller (FNC), placed appropriately by the network administrator, receives information from each AP, such as the number of APs, the number of (source) sensor nodes, the Received Signal Strength Indicator (RSSI) of each sensor node to each AP and the current throughput of each AP. Using these information, the FNC is able to determine whether each AP should be switched on or off through an appropriate request.

The proposed fuzzy-based power saving approach turn off the redundant APs according to, mainly, the traffic load and also the distance of their sensors. The traffic load is closely related to the type of source application implemented in the sensors, which may employ scalar, audio and visual nodes. On the contrary, the distance is not determined by the FNC because each AP is responsible for estimating the distance of its sensors as well as that of neighboring APs up to the coverage region. The AP calculates the average of the estimated distances and it is easy to deduce that a greater average distance implies a higher use of transmission power in APs and sensors. Actually, some works have proposed promising approaches for energy efficiency when adjusting transmission power of sensor nodes [49,50], and such works might exploit our approach for higher efficiency. For this reason, the proposed optimization solution, introduced in the following subsection, aims to switch off the APs with the maximum average distance value because these would increase their transmission power to a greater value if they were turned on.

Packet relaying is too degrading in terms of energy consumption. For instance, for video streaming, intermediate nodes could run out of energy very fast. In order to address this problem, multiple sinks are taken into account in this paper, that are positioned very close to source nodes. In this way it is possible to achieve a 1-hop communication, which removes the need for intermediate nodes and employ Wi-Fi Access Points as sinks. For dense WMSN deployed in infra-structured environments, and assuming high-quality and intensive monitoring, these considerations are reasonable and feasible.

The proposed fuzzy-based solution is characterized by an algorithm, represented in Fig. 2, that handles the switching on/off of the APs and works as follows. In the first step, “Neighbor Discovery”, it is determined whether two APs that belong to the same WLAN can be neighbor of each other. In fact, in a WLAN two APs can be neighbor if they are in close physical proximity of each other. For this reason, in this paper each AP transmits a beacon message periodically and the neighboring APs use it in order to update their “Neighbor table” after receiving n beacons. On the contrary, an AP is removed from the table after m missed beacons. The values of n and m are established in the design phase of the network, but it is easy to deduce that according to the chosen values the network performance change significantly. For example, the table may not be updated appropriately, and then two or more APs possibly are not included, although they are in close physical proximity of each other.

In the “Distance Estimation” step the sensors send a probe request to all channels in order to localize the AP and, as a consequence, each AP can estimates the RSSI (distance). In the next step, “Averaging Distances”, the average distance is determined by the APs based on the results of the previous step. The “Averaging Throughput” block calculates the average throughput. In this way, in the “APs Sorting” step, the APs are ranked based on the average throughput because they will be examined from the first one with the lower throughput to the last. It is necessary to note that these proceedings do not require a substantial computation, imposing low additional overhead.

In the next step, information coming both from the sensors and the APs is provided to a FLC, on the FNC. The output variable is represented by the percentage needed to switch on or off the APs, as depicted in Fig. 3. If the output value is more than 50% (threshold), the AP will be turned off; otherwise, it remains on. These op-

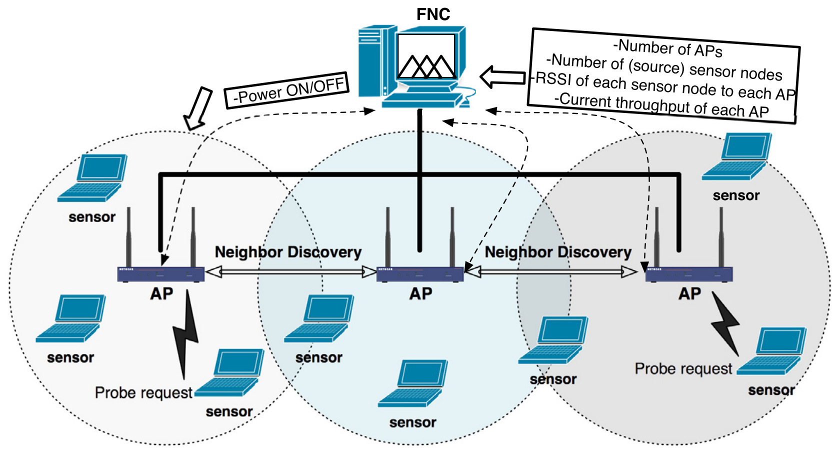

Fig. 1. Proposed network architecture.

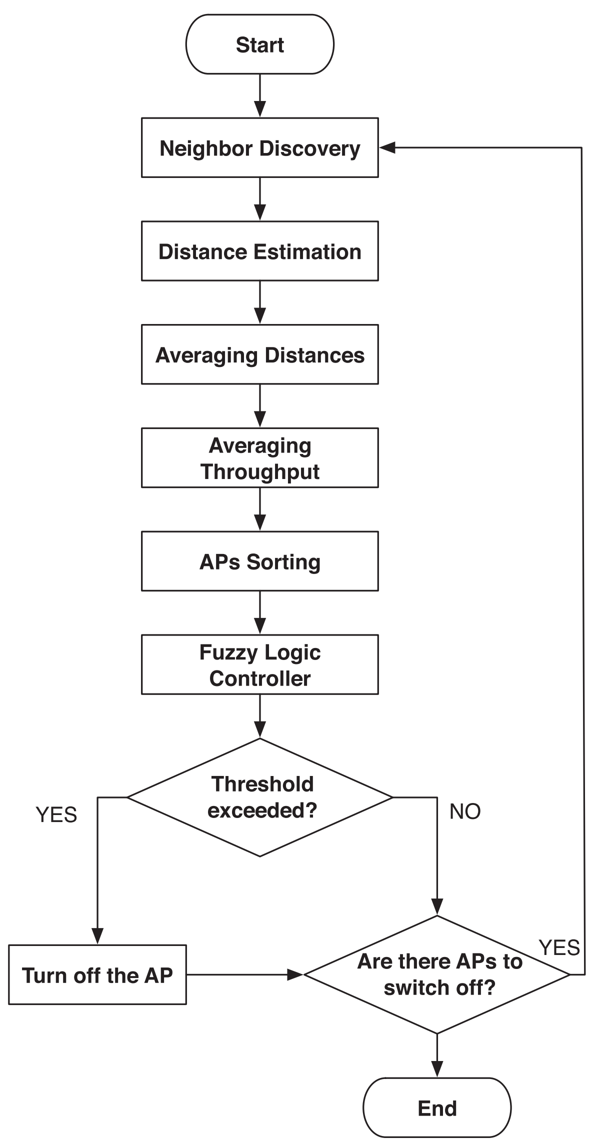

Fig. 2. Proposed algorithm.

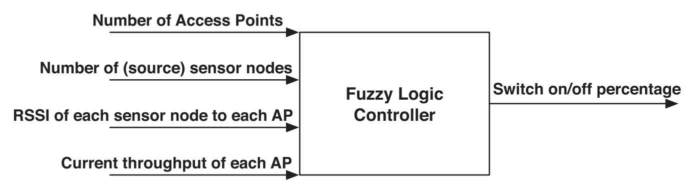

Fig. 3. Proposed fuzzy logic controller.

erations, which in any case are not computationally expensive, are carried out by the FNC in order to further lighten the behavior of APs. So, the "complexity" of the solution introduced in this paper is left only to the FNC.

As known, through fuzzy logic it is possible to identify information with a policy based on sets theory, more flexible than the concept of exclusive membership (classical logic). It introduces the concept of degree of membership of an element to a set. To this end, in this paper three membership functions for each variable (LOW, MEDIUM, HIGH) have been defined. The membership functions have been developed considering these value ranges for the considered input/output variables:

- Input: RSSI of each sensor node to each AP [$-80 \div -40$] dB;
- Input: number of neighbor APs [0÷8];
- Input: number of (source) sensor nodes [0÷254];
- Input: current throughput of each AP [0÷100] %.
- Output: the need to turn on/off the AP [0÷100] %.

As a remark, we consider the throughput of each AP as a percentage of 70% of the theoretically maximum attainable bandwidth of wireless MAC protocols, since the maximum bandwidth is usually never achieved. So, for example, IEEE 802.11g standard provides 54Mbps as the maximum bandwidth, but we only consider 70%(37.8Mbps) of it.

In order to understand how all variables are generically fuzzyfied it is necessary to consider the Fig. 4. The y-axis specifies the degree of membership of the variable to the specific membership function. Considering a generic variable x containing a range of values from the minimum to the maximum value that the variable itself can assume, each membership function can be represented by the generic triangular-shaped membership function [51] as follow:

$$f(x; a, b, c) = \begin{cases} 0 & \text{if } x < a \\ \dfrac{x-a}{b-a} & \text{if } a \le x \le b \\ \dfrac{c-x}{c-b} & \text{if } b \le x \le c \\ 0 & \text{if } x > c \end{cases} \quad (1)$$

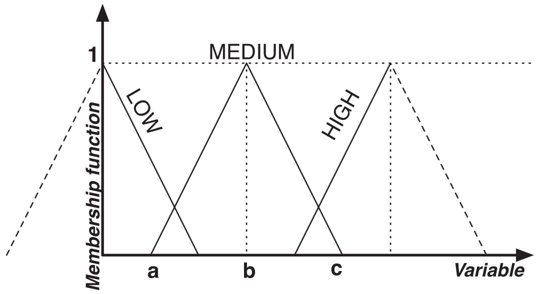

Fig. 4. Triangular membership functions.

Table 1
RSSI of each sensor node to each AP membership function values: x = [−80 ÷ −40] dB.

Membership function	a	b	c
Low	−95	−80	−75
Medium	−70	−60	−50
High	−55	−40	−25

Table 2
Number of neighbor APs membership function values: x = [0÷8].

Membership function	a	b	c
Low	0	1	2
Medium	1	4	7
High	6	8	10

Table 3
Number of (source) sensor nodes membership function values: x = [0÷254].

Membership function	a	b	c
Low	0	5	20
Medium	15	30	45
High	40	147	254

Table 4
Average throughput percentage membership function values: x = [0÷100].

Membership function	a	b	c
Low	0	15	30
Medium	20	40	60
High	50	75	100

Table 5
Percentage need to switch on/off the APs membership function values: x = [0÷100].

Membership function	a	b	c
Low	0	15	30
Medium	25	45	65
High	60	80	100

Furthermore,Tables 1–5 contain all membership function values for RSSI of each sensor node to each AP, number of neighbor APs, number of (source) sensor nodes, current throughput of each AP and the percentage need to switch on/off the APs, respectively. The output value is determined through the fuzzy rules based on IF-THEN controls. If the calculated access point switch on/off percentage is more than the established threshold value (50%), the algorithm starts the switch off procedures.

It is useful to note that the threshold value, 50% in this paper, can be established in the design phase of the network. In this way it is possible to differentiate the settings for each AP. For example, an AP may have both more neighboring APs and more connected users compared to others, while another APs can have less. As it is possible to note in Fig. 2, the algorithm continues with subsequent APs in the list, until less than the half of APs are switched off.

However, once the APs to be switched off have been identified it is not possible to just turn off them, since, even if the traffic is low, a number of sensors may be accessing the candidate AP. For this reason different approaches can be used during this phase. For example, after the switch off decision is taken, the network waits until no sensor is accessing the candidate AP, which is thus turned off only when it is idle. This approach is the least invasive for sensors but involves a drawback. In fact, the time between the switch off decision and the AP becomes idle may be long, thus limiting the effectiveness of the energy saving approach. In another applicable approach, as soon as the switch off decision is taken, no new service requests are accepted by the candidate AP, which can be turned off when all services in progress, at the time of switch off decision, terminate. The delay between the switch off decision and the real off is less than the previous approach, but still significant, because it can be equal to the longest residual time of the services in progress at the decision time. On the contrary, to overcome these problems, the approach proposed in [52] could be employed. Actually, that is an approach for load balancing of the network, but it can also be adopted for the defined scenario herein. In this way, immediately after the switch-off decision is taken, sensors are forced to implement a handover from the AP that is going to be switched off to one of the APs that remain active (a kind of “virtual AP” mechanism). This approach is the most invasive for sensors, but it is useful to note that forced handovers are foreseen by WLAN standards and nowadays almost all devices implement it. At last, as sensors may be streaming real-time traffic, with latency and jitter constraints, handover procedures should be performed carefully. As a solution, no-real-time sensors could make handovers earlier or only them might need to change the AP. Whatever the case, different applications may apply different approaches for sensors handover when APs have to be switched off.

4. Performance evaluation

In order to assess the performance of the proposed approach, several test campaigns have been realized in different real scenarios with varying numbers of APs and sensors. In each iteration of the test campaigns, sensors are placed in the system area based on an uniform deployment and the APs generate traffic according to a Poisson distribution [53]. The packet size has been set to 150kb and the data rate varies from 1Mbps to 20Mbps, considering the IEEE 802.11g mode. Moreover, the duration of the test campaigns has been set in 240 s. The power that is consumed by the APs for the downlink transmission has been considered in order to measure the power consumption. On the contrary, for neighborhood discovery, the APs transmit a beacon signal every 0.05 seconds so that APs in the neighborhood can detect it and add the corresponding AP to the neighborhood APs table for further processing. Furthermore, an active scanning process, where all clients start scanning the channel, has been implemented. It is done through sending multiple probe requests and recording the probe responses (containing BSSID and WLAN SSID). In test campaigns different sources have been considered. More in detail, these sources refer to scalar, audio and video sensors, each of which has different transmission patterns. For this reason, in order to evaluate the performance of the proposed solution, 10 tests were carried out with different transmission patterns. The parameters of test campaigns are summarized in Tables 6 and 7. For instance, considering this last table, in test 1 the sensors transmit at the following rates: scalar 100bps, audio 4kbps and video 128Kbps.

Table 6
Parameters of test campaigns.

Parameter	Value
Traffic model	Poisson
Packet size	150 [kb]
Data rate	from 1 to 20 [Mbps]
Simulation time	240 [s]
Beacon period	0.05 [s]

In the test campaigns, different network conditions have been tested for exactly the same traffic pattern and node positions. The conditions for these verifications are:

- First condition: all APs are powered on with full power;
- Second condition: the APs are turned off randomly;
- Third condition: the APs are managed with the approach proposed by Bhola et al. [40];
- Fourth condition: the APs radio is turned off on the basis of the proposed fuzzy approach.

The assessed values for performance analysis of the network have been the power consumption, that is the whole power required to transmit, to receive and to process signals by the device, and the ratio of Throughput (*Th*), the sum of packets sent by the device, to Workload (*Wl*), the total number of packets that the device has to send. It is necessary to note that in the figures related to the network architecture of both scenarios, the FNC will not be represented for the sake of simplicity. However, as mentioned above and as shown in Fig. 1, the FNC has been used in both scenarios and its functions were performed by a Personal Computer during verifications.

4.1. First scenario

In the first scenario the Cisco/Linksys WRT54GL [54] Routers/APs have been used. These devices are based on a Linux OS and it is therefore possible to execute tasks on them through the OpenWRT firmware [55]. This characteristic makes these devices suitable for the development of the proposed fuzzy-based energy saving system, in which it is necessary to run a specific module on each AP. It is necessary to note that these devices can be programmed to act both as AP, sensors or FNC. However, in this scenario, the Cisco/Linksys WRT54GL Routers/APs have carried out the steps “Neighbor Discovery”, “Distance Estimation”, “Averaging Distances”, “Averaging Throughput” and “APs Sorting” of the proposed algorithm, shown in Section 3, through specific tasks.

In the Case 1 of the first scenario, the network topology, depicted in Fig. 5, is composed by three APs (*AP*0, *AP*1, *AP*2) and seven sensors (from *s*1 to *s*7). The sensors are deployed randomly and the number of heterogeneous sources of test campaign is shown in Table 8. For instance, in test 1, 2 scalar sensors, 1 audio sensor and 4 video sensors have been deployed. In the Case 1 of the first scenario, when the random switch on/off scheme is applied, one between *AP*0 and *AP*2 is switched off randomly. However, this does not happen with the approach proposed in this paper because although *AP*1 may have more connected sensors, they are forced to implement a handover from the AP that is going to be switched off to one of the APs that remain active.

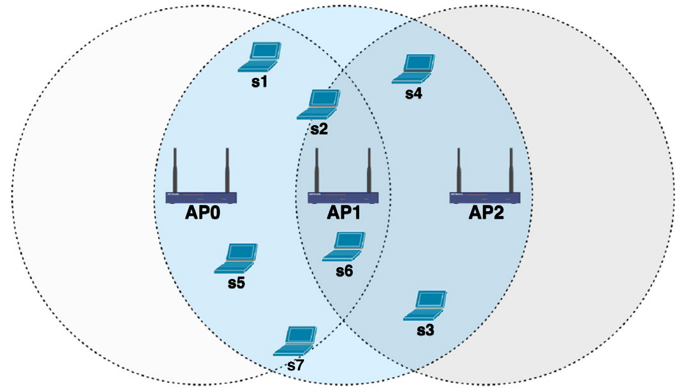

Fig. 5. Network topology in Case 1 of both scenarios.

Table 8
Number of heterogeneous sources of first scenario - Case 1.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Scalar	2	3	1	2	4	2	1	3	4	3
Audio	1	2	3	3	1	2	3	2	2	3
Video	4	2	3	2	2	3	3	2	1	1

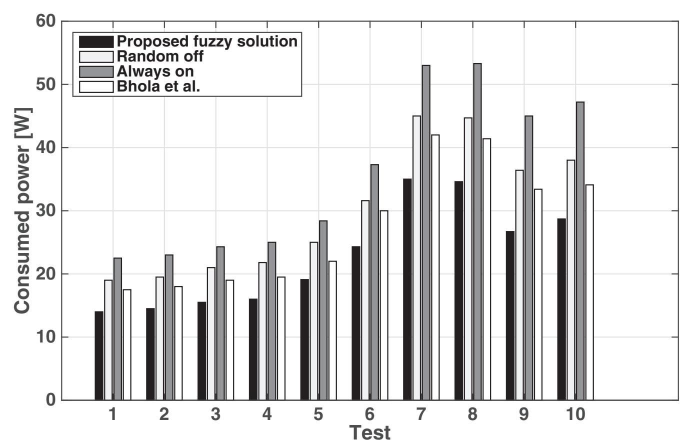

Fig. 6. First scenario - Case 1: measured power consumption.

The results in Fig. 6 show that by using the proposed fuzzy-based approach it is possible to reduce the energy consumption of the whole network. Moreover, assuming that all APs can be switched off for about 12 h during the night in order to save power consumption, at other times of the day the fuzzy-based approach proposed in this work can achieve up to about 40% more efficiency compared to the always on approach, up to about 25% compared to the random switch on/off algorithm and up to about 20% compared to the approach of Bhola et al [40]. It is clear that the worst performance, in terms of power consumption, are obtained by keeping the APs always on. Moreover, compared to Bhola et al., the solution proposed in this paper not only saves more energy but is also significantly less complex in its implementation on real devices. Ob-

Table 7
Transmission patterns of sources in test (T) campaigns.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Scalar [bps]	100	200	300	400	500	600	700	800	900	1000
Audio [Kbps]	4	8	12	16	24	32	40	46	55	64
Video [Mbps]	0.128	0.256	0.512	1	2	4	8	12	16	20

Table 9
Average values of QoS parameters: first scenario - Case 1.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Latency [s]	0.21	0.15	0.18	0.15	0.13	0.17	0.16	0.24	0.23	0.19
Jitter	0.05	0.04	0.03	0.02	0.01	0.03	0.04	0.06	0.04	0.05
Packet loss [%]	3	4	2	2	3	3	4	2	3	4
Handover time [s]	0.20	0.22	0.17	0.18	0.19	0.23	0.19	0.17	0.22	0.21

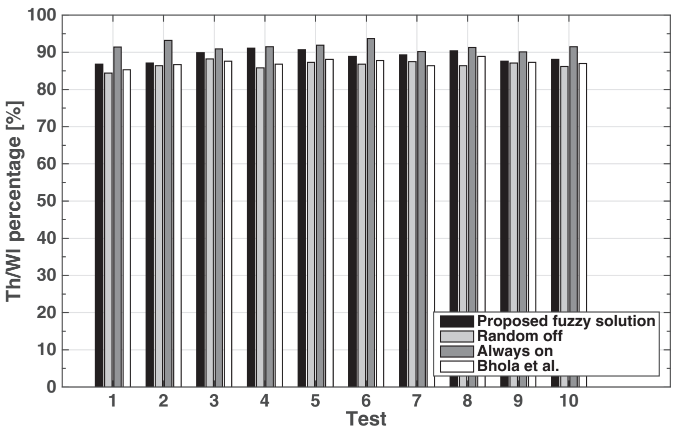

Fig. 7. First scenario - Case 1: Th/Wl behavior.

viously, energy saving was achieved here because deployed sensor nodes were not performing monitoring functions during the night (cameras may be ineffective with low luminosity, depending on their characteristics), while a constant transmission pattern was assumed for the day.

The *Th*/*Wl* behavior achieved by the network is depicted in Fig. 7. The obtained *Th*/*Wl* percentage of the proposed fuzzy approach is about 8% less than the one obtained in the always "on" case. On the contrary, the performance compared to the random off approach are almost better. In a different way, the performance of the proposed solution is always better than the approach introduced by Bhola et al. Anyhow, the small number of drops that occurs compared to the always on approach is caused by the powered off APs. For this reason, although it implements an handover policy, the sensor has to connect to another AP. This mechanism causes a slight decrease in performance. In any case, this may be due to the fact that the network is composed solely of three APs, for which the lack of one of the three affects the *Th*/*Wl* percentage. However, it is useful to remember that the main aim of this work is to obtain a lower power consumption in a dense WMSN and this may be achieved by using the proposed fuzzy based approach.

Considering both the application context of the proposed solution and the transmission patterns of the test campaigns, latency, jitter and packet loss ratio could not be so critical for such tests, since they are not necessarily. However, an handover mechanism is considered in this paper, so they become important. For this reason they have been measured in each test and their average values are shown in Table 9. The obtained results are good and promising. In fact, in all the tests, as previously seen, there have been a very good value of *Th*/*Wl*, and consequently also the QoS parameters are good. The following average values have been measured: latency approximately 0.18 s, jitter about 0.03, packet loss about 3% and handover time about 0.2 s.

The network topology of the Case 2 is represented in Fig. 8. It is composed by nine APs (from *AP*0 to *AP*9) and twelve sensors (from *s*1 to *s*12), hence larger than the Case 1 topology. Even in this case, the sensors are deployed randomly and the number of heterogeneous sources of test campaign is shown in Table 10. For

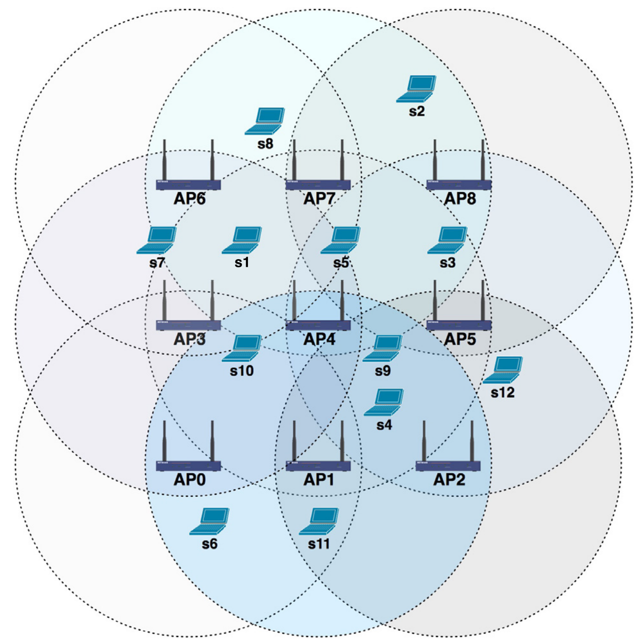

Fig. 8. Network topology in Case 2 of both scenarios.

Table 10
Number of heterogeneous sources of first scenario - Case 2.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Scalar	3	3	5	4	4	5	6	4	7	6
Audio	3	5	2	5	4	4	2	6	2	4
Video	6	4	5	3	4	3	4	2	3	2

instance, in test 7, 6 scalar sensors, 2 audio sensors and 4 video sensors have been deployed. According to the random switch off approach in this case the *AP*3 and *AP*8 are switched off randomly when it is applied. On the contrary, using the proposed algorithm, the *AP*2, *AP*6 and *AP*8 have been switched off according to the output of the fuzzy controller, while the *AP*2, *AP*3 and *AP*5 have been switched off according to the approach of Bhola et al.

The results in Fig. 9 show that using the proposed fuzzy-based approach it is possible to obtain an energy consumption reduction around 40% compared to the always on approach. Moreover, the proposed solution obtains better performance even to the case where the APs are switched off randomly, about 16%, and to the Bhola et al. approach, about 13%, although the number of APs off is the same. Considering the *Th*/*Wl* behavior depicted in Fig. 10, a very small drop has been obtained with the fuzzy approach. In fact, in this case the drop in *Th*/*Wl* percentage has been just about 2% and then the performance of the proposed fuzzy solution are better compared to the Case 1. Network performance are not degraded by turning off the APs and by the use of the handover mechanism. This is due to the fact that the network topology of the Case 2 is constituted by a greater number of APs and then both the turn off of APs and the handover mechanism do not affect the ratio of the sum of packets sent by the device and the total number

Table 11
Average values of QoS parameters: first scenario - Case 2.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Latency [s]	0.28	0.29	0.25	0.24	0.21	0.31	0.28	0.23	0.25	0.28
Jitter	0.08	0.06	0.09	0.05	0.03	0.07	0.09	0.03	0.07	0.05
Packet loss [%]	6	5	5	4	5	8	6	5	5	6
Handover time [s]	0.25	0.28	0.29	0.30	0.22	0.34	0.28	0.23	0.29	0.28

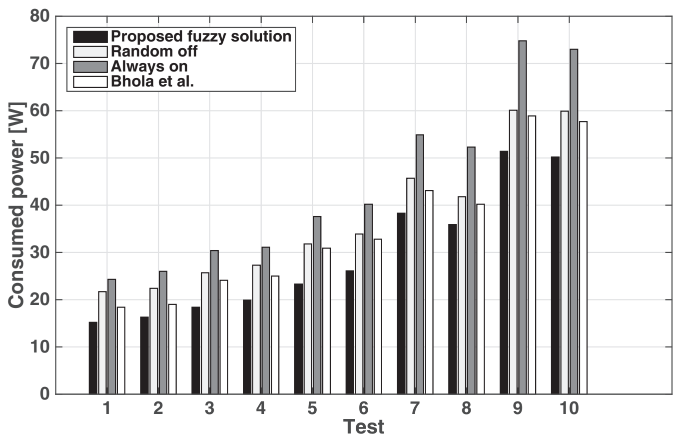

Fig. 9. First scenario - Case 2: measured power consumption.

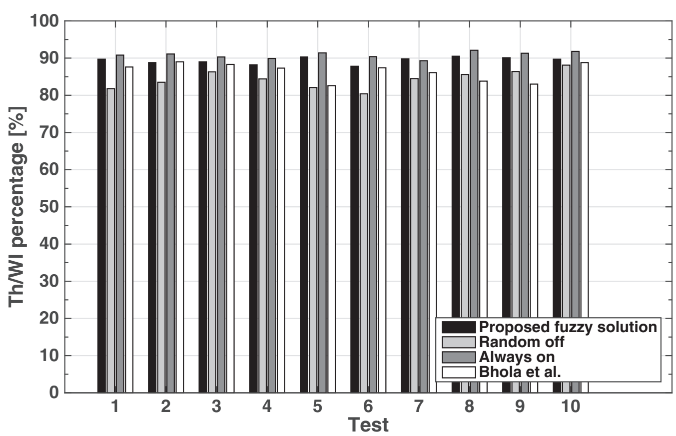

Fig. 10. First scenario - Case 2: Th/Wl behavior.

of packets that the device has to send. The average latency, jitter and packet loss values, measured in test campaigns of Scenario 1 - Case 2, are shown in Table 11. In this case the large number of APs and sensors has resulted in a higher number of handover that has influenced slightly on performance. However, even in Case 2 the behavior of Th/Wl in the various test has been good and then, as a consequence, even those of the QoS parameters, whose average values are 0.26 s for latency, about 0.06 for jitter, about 5.5% for packet loss and about 0.28 s for handover time.

4.2. Second scenario

In the second scenario a model has been built in Simulink/Matlab, as shown in Fig. 11. In detail, the behavior of both the APs and the FNC is managed through the Simulink/Stateflow environment, an internal Matlab tool that allows to describe the evolution of a specific system by means of a finite state machine. The finite state machine related to the AP management is reported in Fig. 12. As shown in Fig. 11 the RSSI of each sensor node to each AP, the Number of neighbor APs, the Number of source sensors nodes and the Current throughput of each AP are acquired as input parameters of the block called “Access point”. In the diagram these are random values, generated through uniform random number blocks, while on the testbed scenario they are obtained through real devices (Wi-Fi devices) connected to the APs. The output values of the “Access point” block are the updated input parameters. In fact, even in this case, as shown in Fig. 3, the FLC processes four input variables. Its behavior is based on the membership functions and inference rules described in the previous Sections.

The model depicted in Fig. 11 has been implemented on the prototyping board that is shown in Fig. 13 through the Embedded Coder integrated in Matlab. Several prototyping boards have been used in the second scenario. The processing unit is the Microchip PIC24FJ256GB108 microcontroller [56], which integrates the control features of a microcontroller unit with the processing and throughput capabilities of a digital signal processor. This 16-bit microcontroller has a maximum processing power of 16 MIPS and offers multiple serial ports (3xI2C, 3xSPI), 4xUARTS and 23 independent timers. The availability of 16kB of RAM memory for buffering, of up to 256kB of enhanced flash program memory and other characteristics make this microcontroller very suitable for embedded control. The prototyping board is equipped with a wireless module compliant to the IEEE 802.11 standard, the Microchip RN171XV [57] module that incorporates an 802.11 b/g radio, a 32 bit processor, a TCP/IP stack, a real-time clock, a crypto accelerator, a power management unit and an analog sensor interface. Moreover, the RN171XV module supports infrastructure networking for worldwide Internet access directly by every node and ad-hoc connectivity for fully connected point to point networks. It is necessary to note that in this case the role of the FNC has not been done by a Personal Computer, but always by a prototyping board properly programmed. Furthermore, it is obvious that the boards used as APs implement the part on the left in Fig. 11 while the board used as FNC the one on the right, i.e. the Fuzzy logic controller. Other prototyping boards have been used as sensors, whose number and type of application are always those shown in Tables 7, 8 and 10. The implementation presented herein is just a proof-of-concept to show the feasibility of the proposed solution on COTS (Commercial Off-The-Shelf) devices.

Even in the second scenario two Cases have been considered, which were the same analyzed in the first scenario whose topologies are shown in Figs. 5 and 8 respectively. Tables 12 and 13 compares the results obtained by our approach with WRT54GL devices [54] (the same as in first scenario of Figs. 6, 7, 9 and 10) with the results obtained by its implementation on the prototyping board in Fig. 13. Moreover, Table 14 shows the obtained average values of QoS parameters in both cases by using the prototyping board. The results in Tables 12–14 show that the model implemented in the prototyping board obtains very good performances. In particular, the consumed power for our system is slightly lower and the Th/Wl percentage for our system is slightly higher than the ones obtained with WRT54GL devices (this is natural, as with the prototyping board some timings that strictly depend on the hardware have been optimized) and much better than the results for the other approaches in Figs. 6, 7, 9 and 10. This conclusion is valid even about obtained values on QoS parameters, which in some

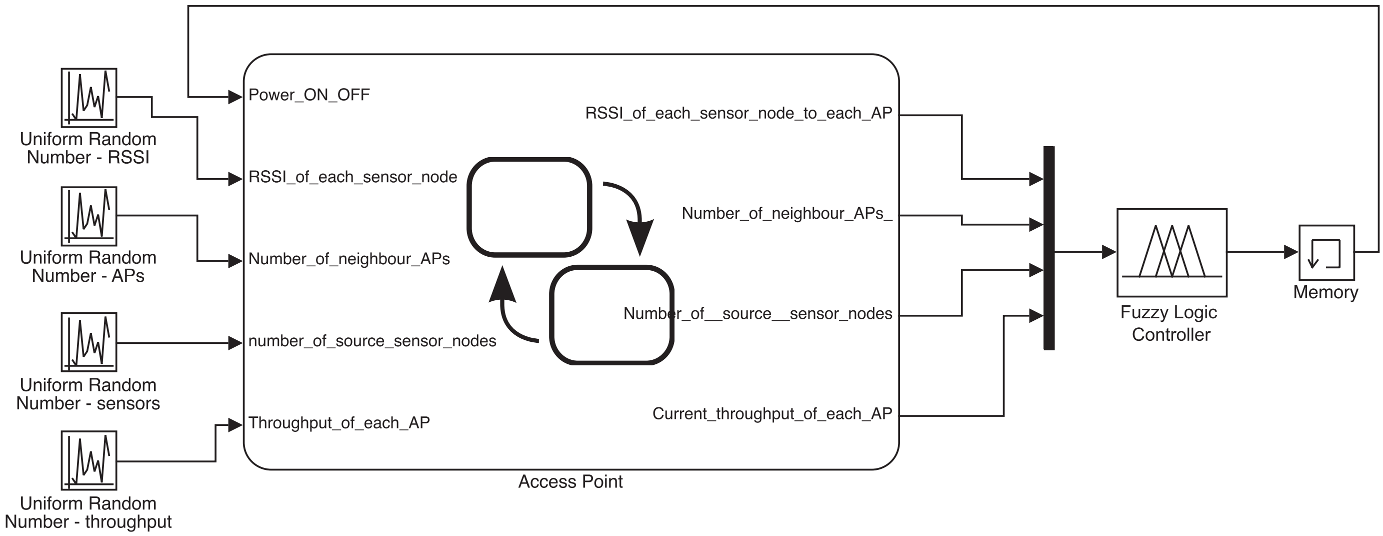

Fig. 11. Simulation model scheme.

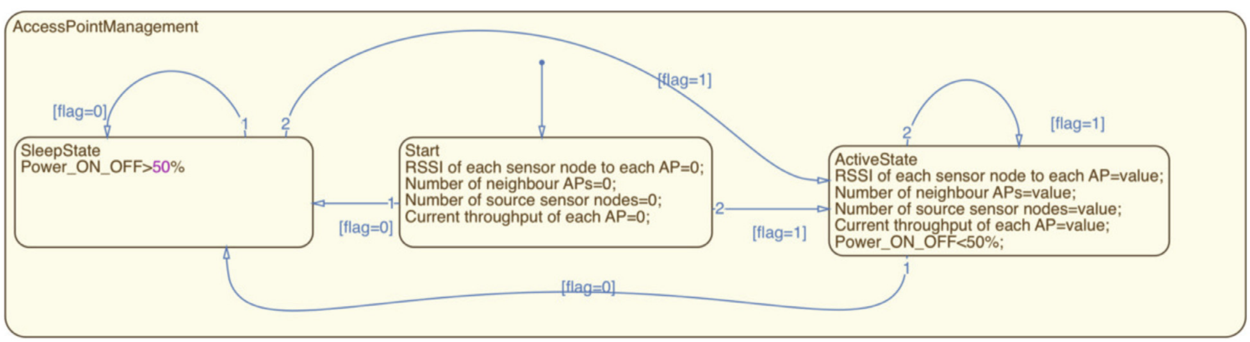

Fig. 12. Access point behavior flow chart.

Table 12
Consumed power in test (T) campaigns of both scenarios.

	Case 1									
Consumed power [W]	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Scenario 1: WRT54GL devices	14.1	14.5	15.5	16.2	19.1	24.3	35.2	34.6	26.7	28.7
Scenario 2: prototyping boards	14.7	15.2	15.1	15.7	18.4	25.5	34.9	35.2	27.3	27.7
	Case 2									
Consumed power [W]	*T1*	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*	*T9*	*T10*
Scenario 1: WRT54GL devices	15.2	16.3	18.4	19.9	23.3	26.1	38.3	35.9	51.4	50.2
Scenario 2: prototyping boards	15.9	16.2	19.4	19.8	22.4	25.5	37.4	38.5	49.8	50.3

Table 13
Th/Wl percentage in test (T) campaigns of both scenarios.

	Case 1									
Th/Wl percentage	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Scenario 1: WRT54GL devices	86.8	87.1	89.9	91.1	90.7	88.9	89.3	90.4	87.6	88.1
Scenario 2: prototyping boards	87.4	88.3	88.5	90.4	91.7	89.3	90.3	90.5	88.4	87.5
	Case 2									
Th/Wl percentage	*T1*	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*	*T9*	*T10*
Scenario 1: WRT54GL devices	89.7	88.8	89.1	88.2	90.3	87.8	89.7	90.5	90.1	89.7
Scenario 2: prototyping boards	90.4	91.2	87.4	89.2	90.1	88.3	88.6	91.2	89.5	88.7

cases are better than WRT54GL devices and slightly worse in others. All these results show that the main objectives of the work are fulfilled, as the system here proposed achieves better performance than other approaches without requiring expensive and complex design and can be therefore implemented on off-the-shelf devices.

So far, we have presented energy savings when Wi-Fi access points are switched off, saving energy of the network as a whole. In fact, we were concerned in optimization in the number of active access points, which may indirectly bring valuable results for dense wireless multimedia sensor networks. Although energy consump-

Table 14
Average QoS parameters values in test (T) campaigns of both scenarios.

	Case 1									
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
Latency [s]	0.20	0.14	0.19	0.18	0.11	0.16	0.15	0.24	0.22	0.21
Jitter	0.04	0.03	0.05	0.04	0.01	0.03	0.02	0.05	0.02	0.06
Packet loss [%]	3	3	4	3	2	2	3	2	2	4
Handover time [s]	0.18	0.20	0.19	0.21	0.18	0.19	0.18	0.18	0.20	0.24
	Case 2									
	T1	*T2*	*T3*	*T4*	*T5*	*T6*	*T7*	*T8*	*T9*	*T10*
Latency [s]	0.25	0.24	0.26	0.23	0.20	0.30	0.29	0.21	0.27	0.29
Jitter	0.06	0.03	0.10	0.04	0.03	0.06	0.10	0.02	0.08	0.08
Packet loss [%]	5	3	6	3	5	6	8	3	6	8
Handover time [s]	0.21	0.23	0.31	0.28	0.21	0.32	0.30	0.22	0.30	0.31

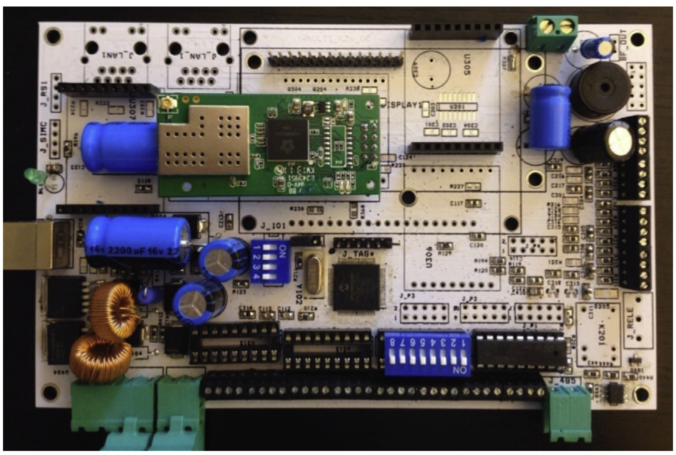

Fig. 13. Hardware board.

tion in sensor nodes are not optimized beyond the fact of using 1-hop communications, the transmission power of sensors might be reduced when closer access points are used, potentially saving energy. Actually, power adjustment is a reasonable approach for wireless sensor networks and there are some research works that have been concerned with this subject [49,50]. Taking the distance to the AP as an optimization parameter, we expect to significantly reduce energy consumption also in sensor nodes, potentially bringing new valuable results. Future works will be concerned with this innovative issue.

5. Conclusions

This paper has presented a fuzzy-based power saving approach in order to switch off unnecessary APs in a dense wireless multimedia sensor networks. In fact, generally a wireless LAN is composed of several APs, each of which provides both a full coverage and, at the same time, redundant resources when traffic load is low. For this reason there is also a waste of electricity. To cope with this problem, a fuzzy solution has been introduced in this work in order to achieve a significant reduction in power consumption without compromising the performance of the network. In fact, in the proposed approach a fuzzy network controller receiving information from each AP, such as a mean of RSSI of probe requests from sensors, a list of neighbour APs, the number of connected sensors and average throughput in access points, determines whether each AP should be switched on or off through fuzzy rules based on IF-THEN controls. If the calculated percentage is more than the established threshold value then the shut-down procedures begin, otherwise the AP stays on.

This work proposes a novel solution that combines several technologies (wireless devices, fuzzy logic control) in an original way so as to obtain a lightweight but effective solution, implementable on COTS devices, that is proven to provide better performance than other approaches in the literature.

The results of test campaigns obtained in the paper clearly demonstrate that the fuzzy-based proposed approach outperforms related works in terms of consumed power and *Th*/*Wl* percentage, especially in large networks. Moreover, the fuzzy-based solution is proven to be very effective in power management of wireless LAN. The designed system fulfills all the targeted design challenges, i.e., flexibility, scalability, lightweight computation and low cost.

The feasibility of the proposed system on real components is proven through an implementation both on the Cisco/Linksys WRT54GL [54] and, particularly, on the Microchip PIC24FJ256GB108 microcontroller [56], a COTS device available at affordable price. Experimental results are both compliant and confirm the effectiveness of the proposed solution. The potential impact of the proposed solution is broad as, being a non-expensive system to realize, it can be extensively and effectively applied in practice.

In the future, the proposed fuzzy-based solution will be tested on networks with higher density and will be optimized in order to improve the power consumption management, and how these impact to the Quality of Service (QoS) of wireless multimedia sensor networks. The fuzzy controller will be tested using different membership functions, such as Gaussian or trapezoidal, in order to determine which of them get better results.

Another direction for future research on the solution here addressed is to augment the proposed approach with a neural network able to forecast the traffic load conditions, i.e., to predict the traffic load conditions at different times of the day or on different days of the week. This combination would allow the fuzzy controller to make its decision taking into account not only the current situation, but also the probable short-term evolution of the traffic load. Moreover, for real-time sensor nodes, proactive approaches could also be employed to predict bursts of multimedia data transmissions, which will require more active APs to be active. For example, the work in [25] employs scalar sensors to rapidly detect critical events, and such detection could be used to active APs that were turned off, potentially reducing undesired latency and jitter.

References

[1] I. Almalkawi, M. Zapata, J. Al-Karaki, J. Morillo-Pozo, Wireless multimedia sensor networks: current trends and future directions, Sensors 10 (2010) 6662–6717.
[2] D.G. Costa, L.A. Guedes, The coverage problem in video-based wireless sensor networks: a survey, Sensors 10 (9) (2010) 8215–8247.
[3] S. Hwang, D. Yu, Data forwarding based on sensor device constraints in wireless multimedia sensor networks, Multim. Tools Appl. 68 (2) (2014) 297–303, doi:10.1007/s11042-012-1064-6.

[4] L. Cheng, Y. Zhang, T. Lin, Q. Ye, Integration of wireless sensor networks, wireless local area networks and the internet, in: IEEE International Conference on Networking, Sensing and Control, 2004, pp. 462–467.
[5] J.J.P.C. Rodrigues, P.A.C.S. Neves, A survey on ip-based wireless sensor network solutions, Int. J. Commun. Syst. 23 (8) (2010) 963–981.
[6] V. Aishwarya, V.F. Enigo, Ip based wireless sensor networks with web interface, in: International Conference on Recent Trends in Information Technology, 2011, pp. 462–466.
[7] R. Piyare, S.R. Lee, Towards internet of things (IOTS): Integration of wireless sensor network to cloud services for data collection and sharing, Int. J. Comput. Netw.Commun. 5 (2013) 59–72.
[8] L. Mainetti, L. Patrono, A. Vilei, Evolution of wireless sensor networks towards the internet of things: a survey, in: International Conference on Software, Telecommunications and Computer Networks, 2011, pp. 1–6.
[9] J. Yu, M. Kim, H.-C. Bang, S.-H. Bae, S.-J. Kim, IoT as a applications: cloud-based building management systems for the internet of things, Multim. Tools Appl. (2015) 1–14, doi:10.1007/s11042-015-2785-0.
[10] A. Monsalve, H.L. Vu, Q.B. Vo, Optimal designs for IEEE 802.15.4 wireless sensor networks, Wirel. Commun. Mob. Comput. 13 (18) (2013) 1681–1692.
[11] V. Vora, T. Brown, High rate video streaming over 802.11n in dense wi-fi environments, in: IEEE Conference on Local Computer Networks, 2010, pp. 1054–1061.
[12] B. Dezfouli, M. Radi, S.A. Razak, T. Hwee-Pink, K.A. Bakar, Modeling low-power wireless communications, J. Netw. Comput. Appl. 51 (2015) 102–126.
[13] A. Rice, S. Hay, Measuring mobile phone energy consumption for 802.11 wireless networking, Pervasive Mob. Comput. 6 (6) (2010) 593–606. Special Issue PerCom 2010.
[14] D.C. Mur, X. rez-Costa, S.S. Ribes, An adaptive solution for wireless LAN distributed power saving modes, Comput. Netw. 53 (18) (2009) 3011–3030.
[15] R. Lacuesta, J. Lloret, M. Garcia, L. Pealver, Two secure and energy-saving spontaneous ad-hoc protocol for wireless mesh client networks, J. Netw. Comput. Appl. 34 (2) (2011) 492–505.
[16] H. Cui, G. Wei, Q. Huang, Y. Yu, A game theoretic approach for power allocation with QoS constraints in wireless multimedia sensor networks, Multim. Tools Appl. 51 (3) (2011) 983–996, doi:10.1007/s11042-009-0426-1.
[17] M. Pickavet, W. Vereecken, S. Demeyer, P. Audenaert, B. Vermeulen, C. Develder, D. Colle, B. Dhoedt, P. Demeester, Worldwide energy needs for ICT: the rise of power-aware networking, in: Advanced Networks and Telecommunication Systems, 2008. ANTS '08. 2nd International Symposium on, 2008, pp. 1–3.
[18] A. Jardosh, G. Iannaccone, K. Papagiannaki, B. Vinnakota, Towards an energy-star WLAN infrastructure, in: Mobile Computing Systems and Applications, 2007. HotMobile 2007. Eighth IEEE Workshop on, 2007, pp. 85–90.
[19] B. Lannoo, Overview of ICT Energy Consumption, Technical Report, Network of Excellence in Internet Science, 2013.
[20] T. Malinovski, V. Trajkovik, Concept for deploying wireless in the enterprise infrastructure: balancing security and positive QoE for the end-users, in: L. Kocarev (Ed.), ICT Innovations 2011, Advances in Intelligent and Soft Computing, 150, Springer Berlin Heidelberg, 2012, pp. 95–105.
[21] A. Jardosh, K. Papagiannaki, E. Belding, K. Almeroth, G. Iannaccone, B. Vinnakota, Green WLANs: on-demand WLANs infrastructures, Mob. Netw. Appl. 14 (6) (2009) 798–814.
[22] S. Diaz, J. Sierra, J. Herrera, The use of earth-air heat exchanger and fuzzy logic control can reduce energy consumption and environmental concerns even more, Energy Build. 65 (0) (2013) 458–463.
[23] M. Seddiki, R.P. de Prado, J.E. Munoz-Exposito, S. Garciáa-Galan, Fuzzy rule-based systems for optimizing power consumption in data centers, in: R. S. Choras (Ed.), Image Processing and Communications Challenges 5, Advances in Intelligent Systems and Computing, 233, Springer International Publishing, 2014, pp. 301–308.
[24] S. Shamshirband, N. Anuar, M. Kiah, V. Rohani, D. Petkovi, S. Misra, A. Khan, Co-FAIS: cooperative fuzzy artificial immune system for detecting intrusion in wireless sensor networks, J. Netw. Comput. Appl. 42 (2014) 102–117.
[25] D.G. Costa, L.A. Guedes, F. Vasques, P. Portugal, Adaptive monitoring relevance in camera networks for critical surveillance applications, Int. J. Distrib. Sensor Netw. 2013 (2013) 1–14.
[26] M. Abazeed, N. Faisal, S. Zubair, A. Ali, Routing protocols for wireless multimedia sensor network: a survey, J. Sensors 2013 (2013) 1–11.
[27] A. Boukerche, Y. Du, J. Feng, R. Pazzi, A reliable synchronous transport protocol for wireless image sensor networks, in: IEEE Symposium on Computers and Communications, 2008, pp. 1083–1089.
[28] D.G. Costa, L.A. Guedes, A survey on multimedia-based cross-layer optimization in visual sensor networks, Sensors 11 (5) (2011) 5439–5468.
[29] J.-H. Lee, I.-B. Jung, Adaptive-compression based congestion control technique for wireless sensor networks, Sensors 10 (4) (2010) 2919–2945.
[30] M. Chen, V. Leung, S. Mao, M. Li, Cross-layer and path priority scheduling based real-time video communications over wireless sensor networks, in: IEEE Vehicular Technology Conference, 2008, pp. 2873–2877.
[31] S. Pudlewski, T. Melodia, A. Prasanna, Compressed-sensing-enabled video streaming for wireless multimedia sensor networks, IEEE Trans. Mob. Comput. 11 (6) (2012) 1060–1072.
[32] J. Zhang, J. Ding, Cross-layer optimization for video streaming over wireless multimedia sensor networks, in: International Conference on Computer Application and System Modeling, 2010, pp. 295–298.
[33] C.M.D. Viegas, F. Vasques, P. Portugal, R. Moraes, Real-time communication in IEEE 802.11s mesh networks: simulation assessment considering the interference of non-real-time traffic sources, EURASIP J. Wirel. Commun. Networking 2014 (2014). Article ID 219, 15
[34] H. Touil, Y. Fakhri, M. Benattou, Energy-efficient MAC protocol based on IEEE 802.11e for wireless multimedia sensor networks, in: International Conference on Multimedia Computing and Systems, 2012, pp. 53–58.
[35] N. Chilamkurti, S. Zeadally, R. Soni, G. Giambene, Wireless multimedia delivery over 802.11e with cross-layer optimization techniques, Multim. Tools Appl. 47 (1) (2010) 189–205.
[36] R. Zhu, J. Wang, Power-efficient spatial reusable channel assignment scheme in WLAN mesh networks, Mob. Netw. Appl. 17 (1) (2012) 53–63.
[37] S.-L. Tsao, C.-H. Huang, A survey of energy efficient MAC protocols for IEEE802.11 WLAN, Comput. Commun. 34 (1) (2011) 54–67.
[38] R. Shaddad, A. Mohammad, A. Al-hetar, Analysis of physical layer performance of hybrid optical-wireless access network, Opt. Commun. 284 (20) (2011) 4894–4899.
[39] L. Bononi, M. Conti, L. Donatiello, A distributed mechanism for power saving in IEEE 802.11 wireless LANs, Mob. Netw. Appl. 6 (3) (2001) 211–222.
[40] A. Bhola, S. Srivastava, C.K. Jha, Energy conservation of access point using caps algorithms, in: Recent Advances and Innovations in Engineering (ICRAIE), 2014, 2014, pp. 1–6.
[41] R. Riggio, T. Rasheed, Toward enterprise virtual power consumption monitoring with joule, in: Network Operations and Management Symposium (NOMS), 2014 IEEE, 2014, pp. 1–6.
[42] D. Qiao, K.G. Shin, Z. Abichar, Energy-conservation in 802.11 WLANs via transmission-strategy-aware airtime allocation, Comput. Netw. 52 (12) (2008) 2280–2291.
[43] M.A. Marsan, M. Meo, Queueing systems to study the energy consumption of a campus WLAN, Comput. Netw. 66 (0) (2014) 82–93.
[44] R. Mathur, M. Sharma, A. Misra, D. Baveja, Energy-efficient deployment of distributed mobile sensor networks using fuzzy logic systems, in: Advances in Computing, Control, Telecommunication Technologies, 2009. ACT '09. International Conference on, 2009, pp. 121–125.
[45] M. Moghimi, J. Venkatesh, P. Zappi, T. Rosing, Context-aware mobile power management using fuzzy inference as a service, in: D. Uhler, K. Mehta, J. Wong (Eds.), Mobile Computing, Applications, and Services, Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, 110, Springer Berlin Heidelberg, 2013, pp. 314–327.
[46] H. Hemi, J. Ghouili, A. Cheriti, A real time fuzzy logic power management strategy for a fuel cell vehicle, Energy Conv. Manag. 80 (0) (2014) 63–70.
[47] H. Bagci, A. Yazici, An energy aware fuzzy approach to unequal clustering in wireless sensor networks, Appl. Soft Comput. 13 (4) (2013) 1741–1749.
[48] Q.-T. Lam, M.-F. Horng, T.-T. Nguyen, J.-N. Lin, J.-P. Hsu, A high energy efficiency approach based on fuzzy clustering topology for long lifetime in wireless sensor networks, in: N.T. Nguyen, B. Trawiski, R. Katarzyniak, G.-S. Jo (Eds.), Advanced Methods for Computational Collective Intelligence, Studies in Computational Intelligence, 457, Springer Berlin Heidelberg, 2013, pp. 367–376.
[49] Y.-T. Chen, M.-F. Horng, C.-C. Lo, S.-C. Chu, J.-S. Pan, B.-Y. Liao, A transmission power optimization with a minimum node degree for energy-efficient wireless sensor networks with full-reachability, Sensors 13 (3) (2013) 3951–3974.
[50] X. Chen, N. Rowe, Saving energy by adjusting transmission power in wireless sensor networks, in: IEEE Global Telecommunications Conference, 2011, pp. 1–5.
[51] H. Preuss, V. Tresp, Neuro-fuzzy, Automatisierungstechnische Praxis (1994) 10–24. In German
[52] M. Collotta, G. Pau, V. Salerno, G. Scata, A distributed load balancing approach for industrial IEEE 802.11 wireless networks, in: Emerging Technologies Factory Automation (ETFA), 2012 IEEE 17th Conference on, 2012, pp. 1–7.
[53] C. Daskalakis, I. Diakonikolas, R.A. Servedio, Learning poisson binomial distributions, CoRR (2011). arXiv: 1107.2702.
[54] Cisco/linksys wi-fi router WRT54GL, http://www.linksys.com/it-eu/products/routers/wrt54gl, (accessed on october 2014).
[55] OpenWrt, https://openwrt.org, (accessed on october 2014).
[56] Microchip, PIC24FJ256GB108 - 16-bit PIC and dsPIC Microcontrollers, Microchip Technology, 2009.
[57] Microchip, RN-171-XV 802.11 b/g Wireless LAN Module, Microchip Technology, 2012.

Mario Collottareceived the Ph.D. degree in 2011 from Catania University, Italy, on the topic of factory automation networks and real-time systems. Since 2010, he has served as an Assistant Professor with tenure with the Faculty of Engineering and Architecture at the Kore University of Enna, Italy. In 2011, he became a principal researcher and director of the Computer Engineering and Network Laboratory. His research interests concern the realization of strategies and innovative algorithms in order to ensure a flexible management of resources in real-time systems and networks. He has published two book chapters and over 70 refereed international journal and conference papers. Dr. Collotta has served on several committees of distinguished journals and international IEEE conferences. He is currently an Associate Editor of several Elsevier and Springer journals. He has also served as a Guest Editor and Lead Guest Editor of several special sections and special issues focused on the study of real-time networks, systems, and applications.

Giovanni Pau a Professor with the Faculty of Engineering and Architecture at the Kore University of Enna, Italy. He received his Bachelor degree in Telematic Engineering from University of Catania, Italy, in 2008; and his Master's degree (cum Laude) in Telematic Engineering and Ph.D. from Kore University of Enna, Italy, in 2010 and 2015, respectively. His research interests include wireless sensor networks, soft computing techniques, home automation and real-time systems. He has participated at several national and international conferences, co-authoring over 30 scientific publications in journals and conferences. Furthermore, he has participated to several research projects funded by industries and research institutes in his research areas. He has served as a member of several committees of distinguished journals and international conferences in his research area, namely, IEEE Transaction on Industrial Informatics, IEEE Transaction on Industrial Electronics, IEEE Journal on Selected Areas in Communications (Series on Green Communications and Networking), IEEE Systems, Elsevier Journal of Computer and System Sciences, Springer Wireless Network, MDPI Sensors, MDPI Energies, etc. He collaborated with the organizing committees of several conferences in order to prepare conference activities, for example, 3rd Symposium on Modeling and Simulation in Computer Sciences and Engineering (2016), IEEE Industrial Electronics and Applications Conference (2016), International Conference on Advances in Computing, Communications and Informatics (2016), Renewable Energy and Green Technology International Conference (2016), IEEE Symposium on Signal Processing and Information Technology (2015), Second International Symposium on Computer Vision and The Internet (2015), and Communication System and Network Technologies (2014), etc. He is currently an Associate Editor of Wireless Communications and Mobile Computing (Hindawi) and Lead Guest Editor of a special issue on Smart Home Energy Management (Energies - MDPI).

Daniel G. Costa is an Associate Professor with the Department of Technology at State University of Feira de Santana, UEFS, Brazil. He received a D.Sc. degree in Electrical and Computing Engineering from Federal University of Rio Grande do Norte (Brazil) in 2013 and a M.Sc. degree from Federal University of Rio Grande do Norte in 2006. He also received a Computer Engineering degree from Federal University of Rio Grande do Norte in 2005 and an Informatics Technology degree from Federal Institute of Rio Grande do Norte (IFRN) in 2003. He spent one year as a visiting researcher at the Faculty of Engineering of the University of Porto, Portugal.